VOLUME III JANUARY, 1938 NUMBER 1

GEOPHYSICS

A Journal of General and Applied Geophysics

A HISTORICAL REVIEW OF ELECTRICAL PROSPECTING METHODS*

W. M. RUST, JR.†

ABSTRACT

The development of electrical prospecting methods from the discoveries of R. W. Fox in 1830 to recent inventions is traced briefly.

The everyday miracles one has come to expect of electricity are so familiar that many people are inclined to believe that anything can be done if we are only clever enough to find the proper method of applying electricity. It is small wonder then that ever and again someone has attempted to apply electricity to the problem of finding valuable objects below the earth's surface. The most hasty study of the literature shows that the number of investigators in this field is very large. Ambronn, who in his "Elements of Geophysics" (1),[1] gives a fairly complete bibliography of geophysical work prior to 1926, lists approximately four hundred articles on electrical prospecting. In recent years articles on electrical prospecting have appeared at the rate of about 100 per year.

I. NATURAL POTENTIAL MEASUREMENTS

The foundations of electrical prospecting were laid in 1830 when the Englishman, R. W. Fox (2), discovered that electrical currents and potentials were associated with certain ore deposits in Cornwall. He made measurements of these potentials and also of the resistivity of certain of the minerals and surrounding rocks. As a result of Fox' work a number of others made similar measurements and proposed the use of these measurements for prospecting. However, the apparatus used by these early electrical prospectors was too crude for practical work.

* Paper Read at the Fall Meeting, Nov. 19, 1937, Houston, Texas. Published by permission of the Board of Directors, Humble Oil and Refining Company.

† Humble Oil and Refining Company, Houston, Texas.

[1] The numbers in parentheses refer to the like-numbered article in the bibliography at the end of the paper.

One difficulty was that two electrodes of slightly different material, or of the same material but placed in ground of slightly different character, will produce potentials even though no potential originally existed between the two points where the electrodes were placed in the ground. Also the current flowing from the electrodes produces a film of gas which changes the resistance of the circuit. This difficulty was first overcome by C. Barus (3) in 1880 by his invention of a non-polarizing electrode which consisted essentially of a metallic rod placed in a porous cup filled with a solution of the sulphate of the metal composing the rod. Barus was able to trace the Comstock lode and to extend it beyond its previously known position. However, the first discovery of a previously unknown ore deposit of commercial value was made in Norway in 1907 by Muenster (4). In 1912 C. Schlumberger (5) entered the field and his company has exploited the measurement of natural potentials throughout the world with commercial success.

The measurements of natural potentials described above applies only to the location of minerals. In 1894 P. Bachmetjew (6) believed he discovered a potential which was not due to minerals but to the motion of ground waters through subsurface sands. He based the explanation of these potentials upon an effect discovered by G. Quincke (7) in 1859 and later studied by Helmholtz (8). When a liquid flows through a permeable material a potential difference is set up across the material. No surface method has been described to employ this effect successfully in locating sands, but it has been widely used in subsurface measurements. In 1929 Schlumberger (9) received a patent on the application of this method to the location of permeable strata traversed by a borehole. In practice the potential measured is the sum of the Quincke potential and electrochemical potentials.

II. POLARIZATION

In the preceding section mention was made of the ill effects of polarization. Recently M. Mueller (10), in 1934, proposed to utilize polarization as a prospecting method. He believes that polarization occurs at the interfaces between successive strata and that the depth to these strata can be determined by polarization measurements with the utilization of extremely small power.

III. TWO-ELECTRODE RESISTANCE MEASUREMENTS

As early as 1883 Fred Brown (11) proposed to find mineral deposits by the measurement of the resistance of the earth between two electrodes. From 1883 to 1906 he received numerous patents on modi-

fications on this method. This method has the advantage of simplicity, but has a serious defect. The resistance of a body of material is directly proportional to the resistivity of the material and to the thickness of the material and inversely proportional to the cross section through which the current flows. It follows therefore, that the effect of the resistivity of a portion of the ground is roughly proportional to the square of the reciprocal of the distance from that portion of the ground to the nearest electrode. That is to say, the ground in the immediate neighborhood of the electrode contributes a large part of the total resistance of the circuit. Consequently, relatively small variations in the resistivity of the ground in the immediate neighborhood of the electrodes exercise an undue effect on the measurements. The two-electrode method therefore, in general, has little value. The chief exception to this statement is in the case where the material surrounding the electrodes is known to be homogeneous. In practice this occurs very seldom. In 1913 Ambronn (12) used a two-electrode method in an application where this condition is fulfilled. He used the method as a well-logging device. In this case one electrode is fixed. Consequently its resistance is unchanged. The other electrode is raised and lowered in a borehole filled with comparatively homogeneous drilling fluid. In this application the variations in resistance are due almost entirely to the variations in resistivity of the formations opposite the moving electrode.

IV. POTENTIAL MAPS

An improvement over the two-electrode resistance measurements was introduced in 1912 by Schlumberger (13). This improvement consists in placing two electrodes in the ground and passing a constant current between them. Then curves on the surface of the ground are located such that all points on the curve are at the same potential. If the earth were homogeneous the resulting curves would have a definite known form. Any deviation from this form must be due to subsurface variations. The amount of deviation is indicative of the amount of subsurface variation. In 1918 Lundberg (14) proposed a modification of the potential method which simplifies the interpretation of the data. Instead of employing point electrodes as used by Schlumberger, Lundberg employs long linear electrodes, the two electrodes being parallel. For homogeneous subsurface conditions the resulting equipotential curves will be straight parallel lines. In 1930 Nichols and Williston (15) patented a generalization of the potential map method in which the current is passed into the ground by some configuration of electrodes and the displacement of a predetermined

"potential characteristic" from the position it would have had, had the subsurface been homogeneous, is measured.

V. APPARENT RESISTIVITY MEASUREMENTS

The potential map methods have the advantage of giving a graphic representation of the effect of subsurface anomalies but have the serious disadvantage of not being amenable to numerical representation nor to calculations. In 1916 F. Wenner (16) introduced a method which overcomes this difficulty. Wenner passes current into the ground between two electrodes and measures the potential difference between two other electrodes. It is simple to calculate the potential due to any current for any electrode configuration in a homogeneous earth of known resistivity. Knowing the current and potential we are therefore able to determine what would have been the resistivity of the earth if it had been homogeneous. This resistivity is spoken of as the "apparent resistivity." In practice the apparent resistivity is determined for a number of electrode configurations and, in simple cases, this permits one to compute the depth and thickness of the various subsurface strata. In the configuration most commonly used, the four electrodes are in a straight line and equally spaced. This configuration was used in 1925 by Gish and Rooney (17) who introduced the use of a periodically reversed direct current. A similar method was also used in 1925 by Schlumberger (18). In 1929 Schlumberger (19) applied a modification of this method to well-logging. In this method one current electrode remains at the surface and the other three electrodes are lowered into the borehole.

VI. ALTERNATING CURRENT EQUIPOTENTIAL MAPS

The methods previously discussed employ direct current for the measurements. Direct current measurements have certain advantages over alternating current measurements. Direct currents may be obtained by the use of batteries, thus avoiding the necessity of motor driven equipment. Direct current measurements are free from inductive and capacitative effects which are associated with alternating current measurements. On the other hand, alternating current measurements offer advantages which are lacking in direct current measurements. A greater freedom of choice of measurements is available; thus in addition to amplitude measurements—which are the only measurements that can be made with direct currents—one can measure phase relations and magnetic effects. Moreover, the current can

be introduced into the ground either conductively, by the use of electrodes, or inductively, by the use of a loop of wire. An additional advantage is the ease with which alternating currents can be detected by the use of telephone receivers and amplified by the use of vacuum tubes. The first to propose the use of alternating currents were Daft and Williams (20) in 1900. Daft and Williams proposed an equipotential map method using alternating current and telephone receivers. In 1906 Petersson (21) introduced the method into Sweden where it has since been widely practiced. The first commercial success of the method was in 1914 when Bergstrom (22) successfully found new ore deposits. The use of vacuum tube amplifiers was introduced in 1918 by Lundberg (23). H. Hunkel (24), in 1924, was the first to propose the use of phase measurements in alternating current prospecting.

VII. MAGNETIC EFFECT

Schilowsky (25), in 1913, was the first to study the magnetic effect of subsurface anomalies. In 1918 Conklin (26) modified his method by introducing the current into ground inductively instead of conductively. In 1922 Sundberg (27) introduced this method into Sweden.

VIII. RADIO FREQUENCY MEASUREMENTS

The use of currents of radio frequency for prospecting has been proposed by a number of inventors and is frequently the subject of Sunday supplement articles. The first publications on this method were in 1910 by Leimbach and Löwy (28). An interesting modification of this method was patented in 1924 by Löwy (29). This method which Löwy terms "electroaviatic" depends upon the determination of the effect of subsurface anomalies on the properties of an antenna suspended from a balloon which travels over the region to be explored.

IX. TRANSIENTS

A recently proposed method which has met with some success employs electrical transients and was patented by L. W. Blau (30) in 1933. In the transient method a sudden, extremely sharp pulse of current is introduced into the ground by completing the circuit consisting of the ground, electrodes, connecting wires and batteries. The potential at some distance from the current electrodes is observed. This potential does not build up as rapidly as the current, several thousandths of a second being usually required for this building up or transient effect. The manner in which the potential builds up depends upon the subsurface conditions. Since a transient is the equiva-

lent of a current containing all frequencies it is possible from sufficiently accurate measurements on transients to determine the behavior of an electrical system at any frequency, therefore, any information obtainable by the use of direct currents and of alternating currents of any frequencies may be obtained by transient measurements.

In 1935 J. J. Jakosky patented a method which appears to differ only slightly from the Blau method. The method seems to differ in two respects. Instead of an extremely sharp current pulse, a pulse with somewhat slower rate of build up is used and only the "time integrated" effect of the pulse is measured.

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ON THE EXTENSION OF TWO-LAYER METHODS OF INTERPRETATION OF EARTH RESISTIVITY DATA TO THREE AND MORE LAYERS*

ROBERT J. WATSON† AND JAMES F. JOHNSON‡

ABSTRACT

The two-layer problem has been solved completely. Considerable success with the three-layer problem has been attained by the extension of the two-layer methods of Tagg and Roman making use of the principle established by Hummel.

Some of the limitations of these methods are examined by the comparison of theoretical curves for various values of h_2, ρ_2, and ρ_3 with help-curves computed using Hummel's principle. In general it is found that the three-layer problem of the type where a good conductor lies between two relatively poor conductors is more favorable for interpretation by the extension methods than is the opposite case where a poor conductor lies between two good conductors. The disadvantage in the latter case is that the field measurements must be carried to very much larger electrode spacings compared to the depth investigated.

In all three-layer problems where $h_2 < h_1$, a good interpretation for h_1 is difficult. The four-layer problem is much more difficult and only very special types lend themselves to the extension methods.

The use of a large number of theoretical curves for curve matching is advocated both as a supplement to the extension methods and as a more powerful but slower method for the less favorable three-layer problems as well as for problems of four or more layers.

INTRODUCTION

The two-layer problem in resistivity prospecting has been solved completely. The problem of three or more layers is still in an unsatisfactory state although much progress has been made toward the solution of many three-layer problems by extensions of two-layer methods. These extensions have important limitations and some of these are discussed in this paper.

RESISTIVITY PROSPECTING

The electrode configuration most commonly used to determine depths to underlying beds is one credited to Neuman and Wenner.[1] The modification, proposed by Lee,[2] of adding a third potential electrode at the center of the configuration is also much in use. This partitioning method makes possible two separate measurements of

* Paper read at the Fall Meeting, Houston, Texas, Nov. 19, 1937.

† The Carter Oil Company, Tulsa, Oklahoma.

‡ Continental Oil Company, Tulsa, Oklahoma.

[1] Wenner, F.: U. S. Bureau of Standards, Scientific Paper 258 (1915), 469–478.

[2] F. W. Lee, J. W. Joyce and P. Boyer: U. S. Bureau of Mines Inf. Circ. 6171 (1929).

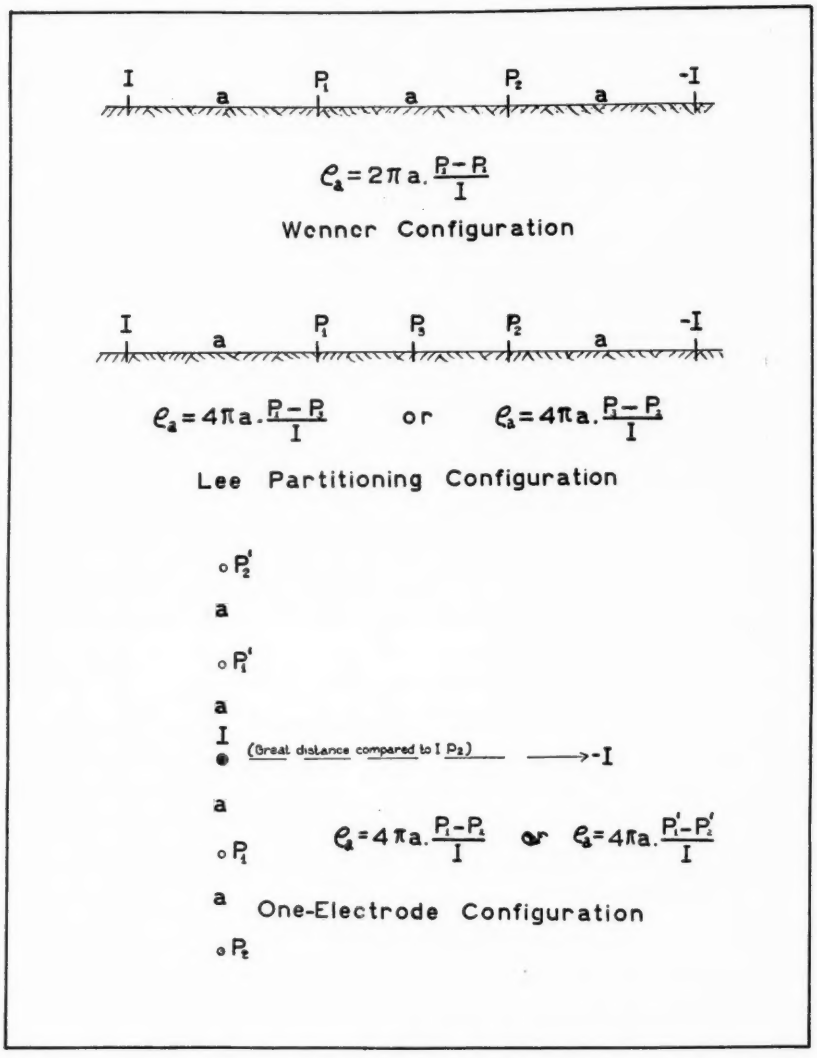

FIG. 1. Three commonly used electrode configurations.

potential at a station which are of aid in determining whether or not the resistivity curves are due essentially to vertical discontinuities. The One Electrode method, described by Ehrenburg and Watson,[3] is also simple and has the practical advantage of requiring less moving

[3] D. O. Ehrenburg and R. J. Watson: Transactions A.I.M.E. (1932), 97,423.

of electrodes. By running the line of potential electrodes in more than one direction a check can be made on the presence of lateral discontinuities in resistivity. This is valuable in assessing the resistivity data for interpretation. Fig. 1 shows the three above-mentioned configurations and the simple formulas by which the apparent resistivity for a given electrode spacing is computed.

Other configurations have been used and found to have particular advantages. The contents of this paper however refer especially to the three above-mentioned methods inasmuch as they are closely related and for homogeneous, horizontal and parallel layers, should give the same value for earth resistivity when the distances between a current electrode and the nearest potential electrode are the same.

METHODS OF INTERPRETATION

The apparent resistivity obtained from field measurements is plotted against the electrode spacing a. The resistivity curves thus made may be divided roughly into two types. The first type is irregular with sharp maxima and minima. The second type is relatively smooth with few and comparatively broad maxima and minima. The interpretation methods used depend on the type of resistivity curve available. With curves which are highly irregular the mathematical methods fail since these methods presuppose an underground made up of essentially flat parallel layers of different resistivity which cannot possibly give the irregular type of curve for simple ohmic conduction. With relatively smooth curves the mathematical methods are applied. The present paper is concerned with interpretations of these smooth curves.

In connection with the use of the mathematical method of interpretation it should be emphasized that the field technique should be such as to prove to the interpreter beyond a doubt that the shape of the resistivity curve is due essentially to vertical discontinuities. Such tests as those described above in connection with the various electrode configurations will give this information.

A number of authors[4] have shown that with the Wenner, Lee and

[4] M. Muskat: Physics (1933), 4, 129–147.
L. V. King: Proceedings of the Royal Society London (1933), 139, 237–277.
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D. O. Ehrenburg and R. J. Watson: Transactions A.I.M.E. (1932), 97, 423.
R. J. Watson: Transactions A.I.M.E. (1934), 110, pp. 201–232.

One Electrode configurations the apparent resistivity determined from surface potential measurements can be expressed by the following equation:

$$\rho_a = \rho_1(1 + 4F) = \rho_1 M, \tag{1}$$

where ρ_a is the apparent resistivity for electrode spacing a, ρ_1 the resistivity of the top layer; F is a function of a, the thickness of the various beds, and the ratios of resistivities of the beds. An expression for the apparent resistivity for any number of layers of any resistivity has been given by Ehrenburg and Watson, in the form of a series. The convergent properties of this expression are not always convenient but with persistence the resistivity curves can be obtained. The curves presented in this paper have been computed with this expression.

The expression for two layers is much simpler and F is a function of a, h, and k where

$$k = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}. \tag{2}$$

Roman[5] has suggested a neat method of interpreting completely the two-layer problem. Since $\rho_a = \rho_1 M$,

$$\log M = \log \rho_a - \log \rho_1$$

also

$$\log a/h = \log a - \log h.$$

A set of master curves can be made by plotting log M against log a/h for various values of k. Now, for a particular field problem, ρ_1 and h are taken to be constant. The field curve obtained by plotting log ρ_a against log a will be the same as by plotting log M (really log ρ_a − log ρ_1) against (log a − log h) except for a shift of the origin of coordinates. If the field curve is placed over a set of theoretical curves and a fit made for a particular value of k, the relations of the origins of the field and theoretical curves give the values of ρ_1, h, and k. A slight practical modification of Roman's original method is to plot the master set of theoretical curves and the field curves on the same type of logarithmic paper.

Tagg[6] accomplishes the same result by a method which is essentially the graphical solution of the equation for ρ_a,

[5] I. Roman: Transactions A.I.M.E. (1934), 110, pp. 183–197.

[6] G. F. Tagg: Transactions A.I.M.E. (1934), 110, pp. 135–145.

$$\rho_a = \rho_1(1 + 4F), \qquad F = f(a, h, k).$$

The three knowns are ρ_1, ρ_a and a. The two unknowns are h and k. In a more recent paper Tagg[7] proposes a modified method which obtains h and k independent of ρ_1.

The extension of these two-layer methods to three layer has been proposed by Manhart, Pirson, Tagg, Kihlstedt and others.[8]

All these extensions are based on an important contribution by Hummel.[9] He showed that in problems involving more than two layers, for electrode spacings large compared to the thickness of these two layers, the top two layers could be combined to give a composite resistivity. Thus for large electrode spacings, the two top layers are combined and the three layers problem becomes one of two layers. The object then is to find the depth of the two top layers taken together. The methods of Roman or Tagg applied to the data obtained by using large electrode spacings will give (h_1+h_2), ρ_1' the composite resistivity and k'. But since

$$k' = \frac{\rho_3 - \rho_1'}{\rho_3 + \rho_1'}, \quad \rho_3 \text{ can also be determined.}$$

In Fig. 2 the method of Roman is shown applied to a three layer problem. In the upper figure the values of ρ_1, h and k are determined, in the lower figure the values of (h_1+h_2), ρ_1' and k'.

The same resistivity curve of Fig. 2 is shown again in Fig. 3 with two help-curves, obtained by the use of Hummel's principle. The first help-curve, for small electrode spacings, is computed on the assumption that h_2 is infinite, and the second help-curve for the larger electrode spacings on the assumption that h_1 and h_2 are combined in resistivity.

It seems clear that the quality of the depth determination of h_1 by Roman's method, made from the first part of the resistivity curve, depends on how near and how effective is the third layer since it causes the real resistivity curve to stop tracking the first help-curve. The length of the electrode spacing over which the resistivity curve tracks

[7] G. F. Tagg: Mining Magazine, London, Vol. 53, No. 3 (1935), pp. 148–154.

[8] T. A. Manhart: Colorado School of Mines Quarterly, Vol. 32, No. 1, 1937.
S. Person: Transactions A.I.M.E. (1934), 110, pp. 148–158.
G. F. Tagg: Mining Magazine, London, Vol. 53, No. 3, 1935.
F. Kihlstedt: Discussion of Roman's paper. Transactions A.I.M.E. (1934), 110.
K. Sundberg: Discussion of Tagg's paper, Transactions A.I.M.E. (1934), 110.

[9] J. N. Hummel: Op. Cit.

the help-curve is a criterion of a good interpretation. The determination of (h_1+h_2) is made from the part of the resistivity curve obtained from larger electrode spacings. In accordance with Hummel, the resistivity curve joins and tracks the second help-curve computed on the assumption that the two top layers give a composite resistivity.

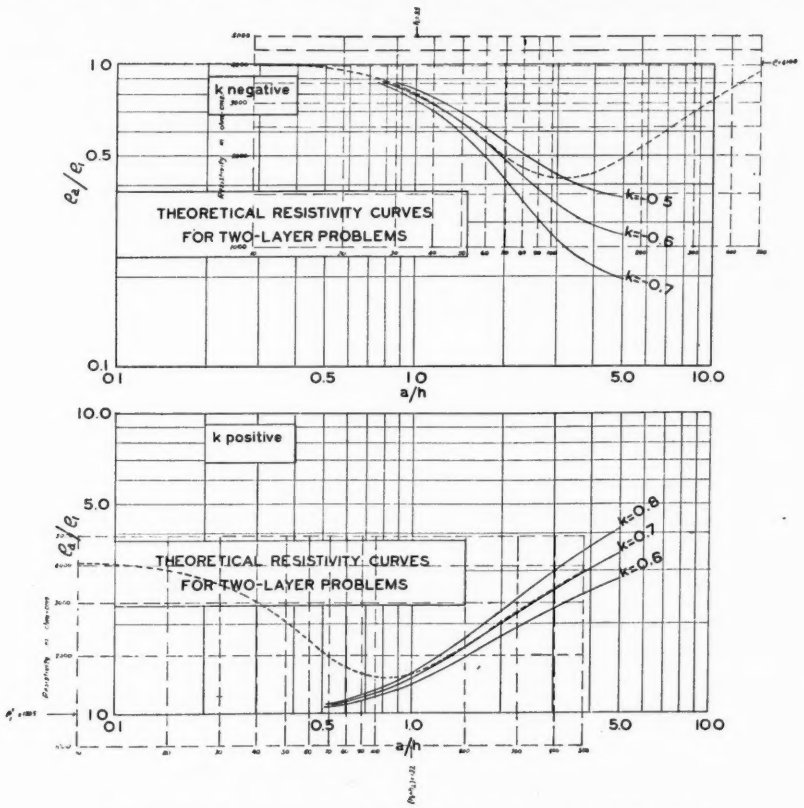


FIG. 2. The Roman method of interpretation for h_1 and (h_1+h_2).

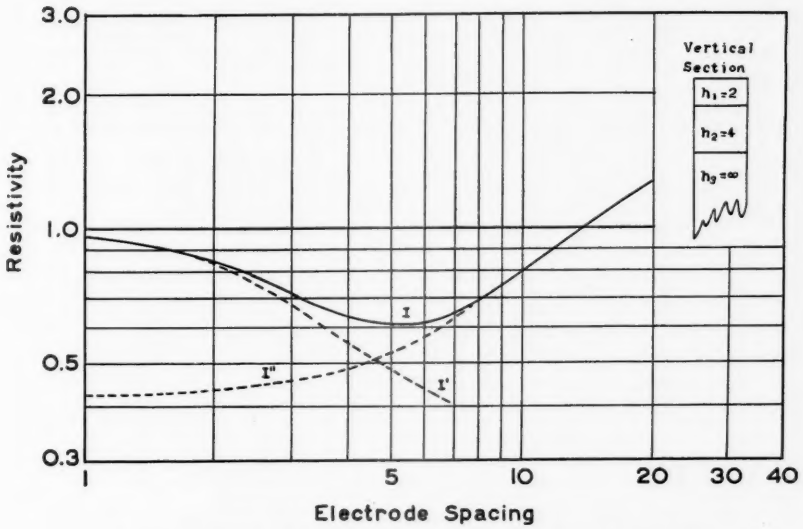
Again it is clear that the length of the electrode spacing over which the resistivity curve tracks the help-curve indicates the possibility of a good depth interpretation.

Figs. 4, 5, 6, 7, 8, and 9 show computed curves for a number of variations of h_2, ρ_2 and ρ_3 together with the help-curves. The curves are for $h_1 \leqq h_2 < h_3$ and $\rho_1 \lesseqgtr \rho_2 \gtreqless \rho_3$. These are conditions which give resistivity curves with one maximum or one minimum. The following variations in resistivity have been used

$\rho_1:\rho_2:\rho_3$ is 1:1/3:3 or 1:3:1/3

1:1/19:3 or 1:19:2.11

and h_2 varies from h_1 to $4h_1$. This set of computed data, while quite incomplete, gives some idea of the three-layer problems which do or do not lend themselves to an interpretation by the extension of Roman's or Tagg's methods.



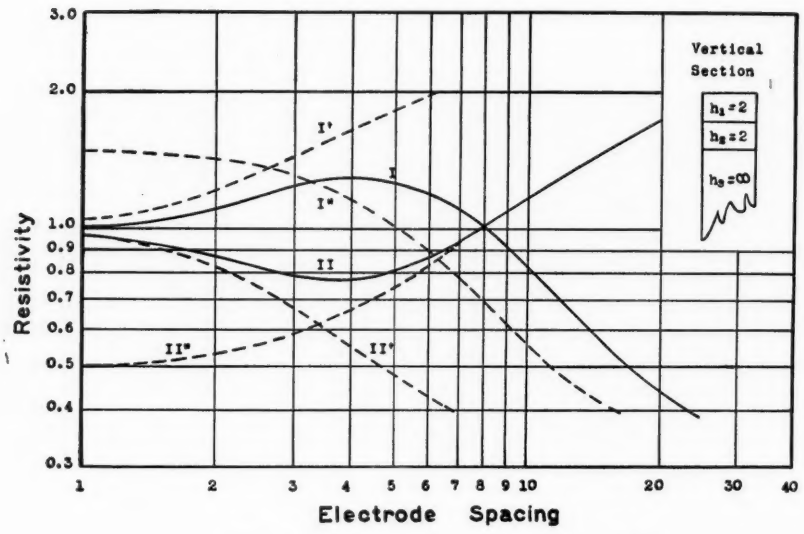
Curve I. Resistivity curve for $\rho_1 = 1$, $\rho_2 = 1/3$, $\rho_3 = 3$

Curve I'. "Help curve" assuming a two-layer problem by letting $h_2 = \infty$.

Curve I''. "Help curve" assuming a two-layer problem by combining the two top layers.

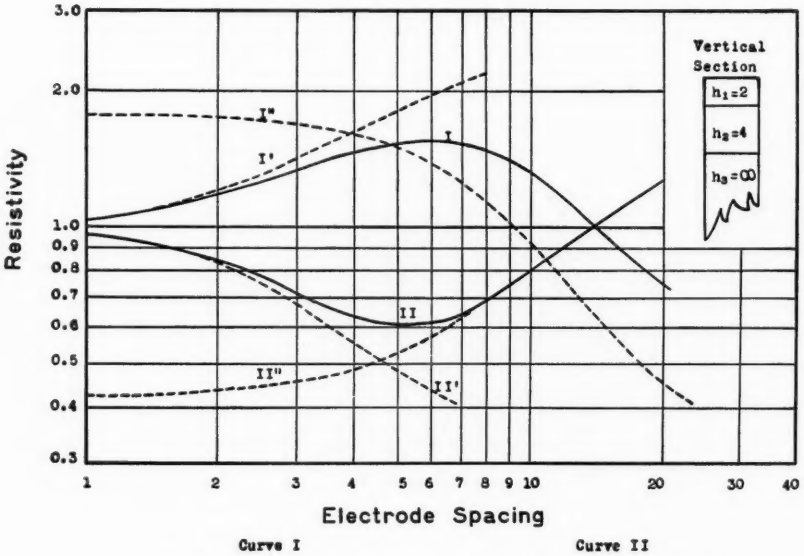
FIG. 3. Resistivity curve with help-curves.

After study of these curves some observations concerning the types of three layer problems favorable to interpretation by the extension methods can be made. In all the cases where $h_1 = h_2$, it would appear that the influence of the lower third layer becomes so large even for small electrode spacings that a good interpretation is not likely. Of these unfavorable types the most favorable are those in which the second layer is a very good conductor or resistor in comparison with the top layer. Extrapolating to the cases where h_1 is larger than h_2, the chance for a good determination of h_1 is even poorer. As h_2 in-



Curve I
$\rho_1 = 1, \rho_2 = 3, \rho_3 = 1/3$

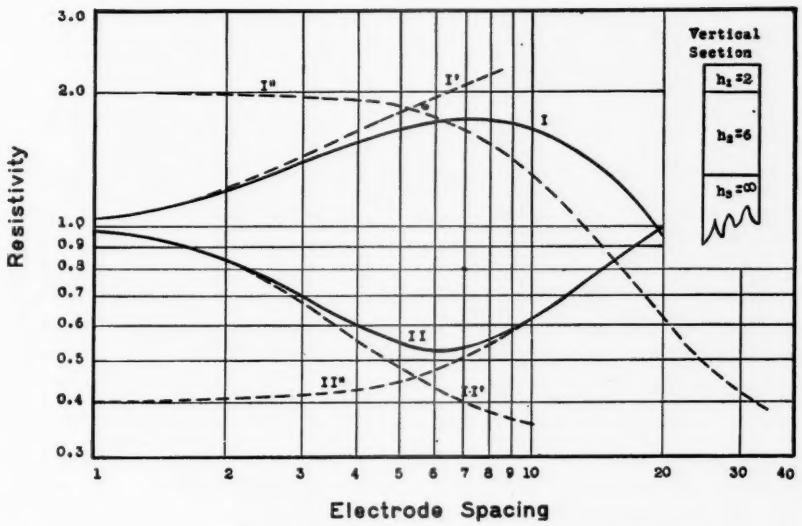
Curve II
$\rho_1 = 1, \rho_2 = 1/3, \rho_3 = 3$



Curve I
$\rho_1 = 1, \rho_2 = 3, \rho_3 = 1/3$

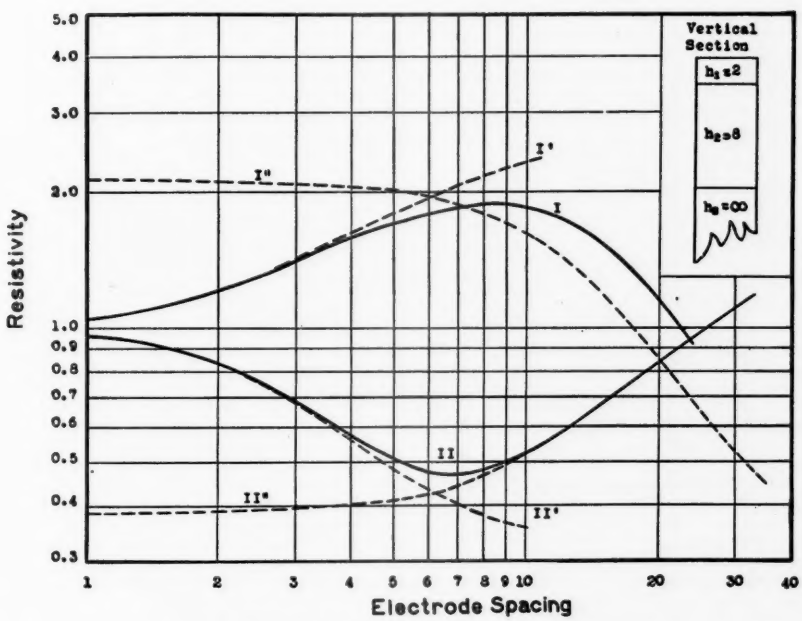
Curve II
$\rho_1 = 1, \rho_2 = 1/3, \rho_3 = 3$

FIG. 4. Three-layer resistivity curves for $\left\{\begin{matrix}\rho_2 = 1/3\ \rho_1 \text{ or } 3\rho_1;\ \rho_1 = 3\rho_1 \text{ or } 1/3\ \rho_1 \\ h_2 = h_1 \text{ and } h_2 = 2h_1.\end{matrix}\right\}$.



Curve I
$\rho_1 = 1, \rho_2 = 3, \rho_3 = 1/3$

Curve II
$\rho_1 = 1, \rho_2 = 1/3, \rho_3 = 3$



Curve I
$\rho_1 = 1, \rho_2 = 1/3, \rho_3 = 3$

Curve II
$\rho_1 = 1, \rho_2 = 3, \rho_3 = 1/3$

FIG. 5. Three-layer resistivity curves for $\left\{\begin{matrix}\rho_2 = 1/3\ \rho_1 \text{ or } 3\rho_2;\ \rho_1 = 3\rho_1 \text{ or } 1/3\ \rho_1 \\ h_2 = 3h_1 \text{ and } h_2 = 4h_1.\end{matrix}\right\}$.

creases compared to h_1 the possibilities of a good determination increase so that when h_2 is three or four times h_1, a good interpretation can be made, especially if ρ_2 is very much larger or smaller than ρ_1. However, the advantage gained in the determination of h_1 due to a

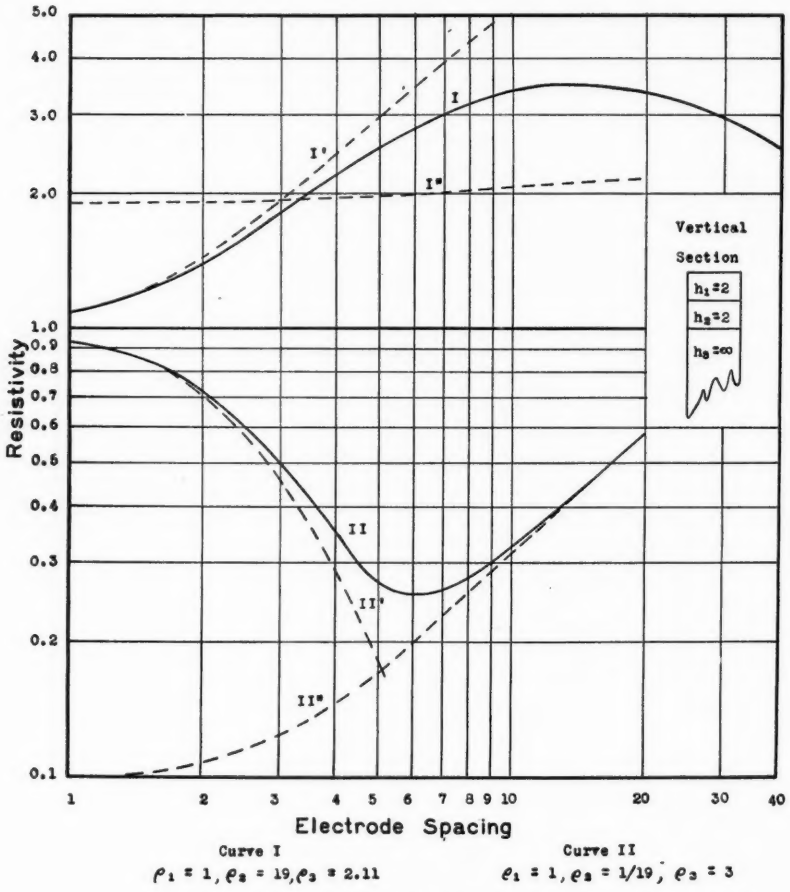


FIG. 6. Three-layer resistivity curves for $\left\{\begin{matrix}\rho_2 = 1/19\,\rho_1 \text{ or } 19\rho_1;\ \rho_3 = 3\rho_1 \text{ or } 2.11\rho_1 \\ h_2 = h_1.\end{matrix}\right\}$

large ratio of resistivity between h_1 and h_2 is offset by the larger electrode spacings necessary for a good interpretation of (h_1+h_2).

In the determination of (h_1+h_2), the superiority of the three-layer problem with the middle layer the better conductor becomes very evident. Even when the ratio of resistivity between h_1 and h_2 is quite

large the resistivity curve joins and tracks with the help curve at a reasonable electrode spacing. In the case where the middle layer is the better resistor very large electrode spacings are required and there are

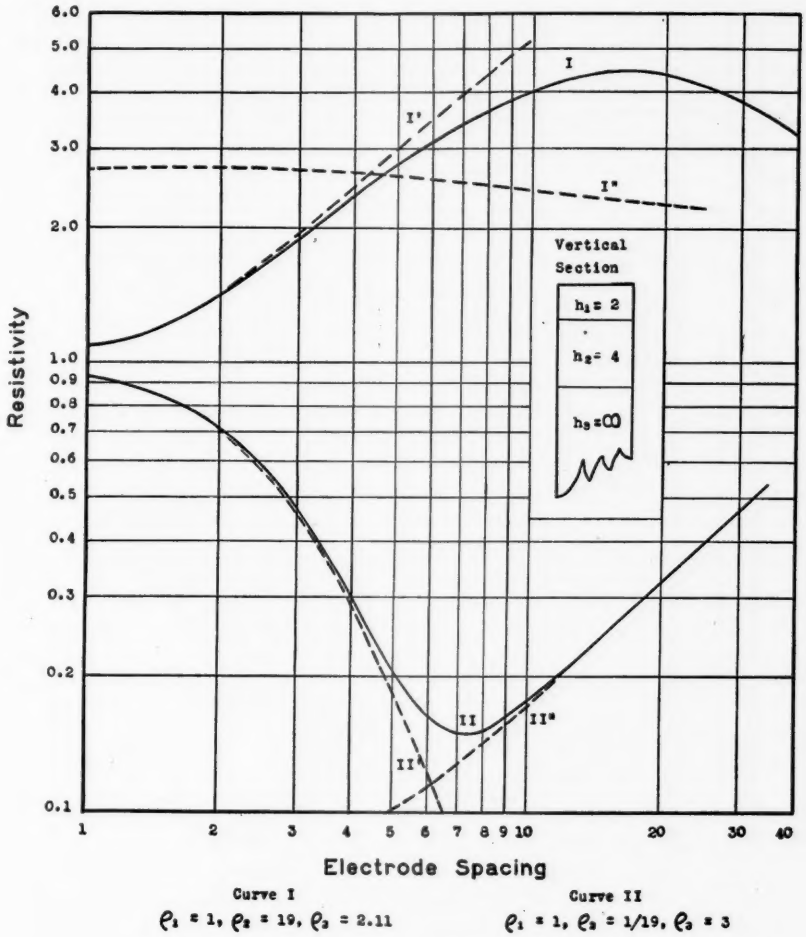


FIG. 7. Three layer resistivity curves for $\left\{\begin{matrix}\rho_2 = 1/19\rho_1, \text{ or } 19\rho_1; \rho_3 = 3\rho_1 \text{ or } 2.11\rho_1 \\ h_2 = 2h_1.\end{matrix}\right\}$.

practical and economic limitations to the length of electrode spacings in many terrains where lateral changes and topographic conditions play a big part.

Where very large electrode spacings can be used, it would seem

possible to find the depth to the thick lowest layer, of homogeneous resistivity, regardless of the number and resistivities of the small layers above.

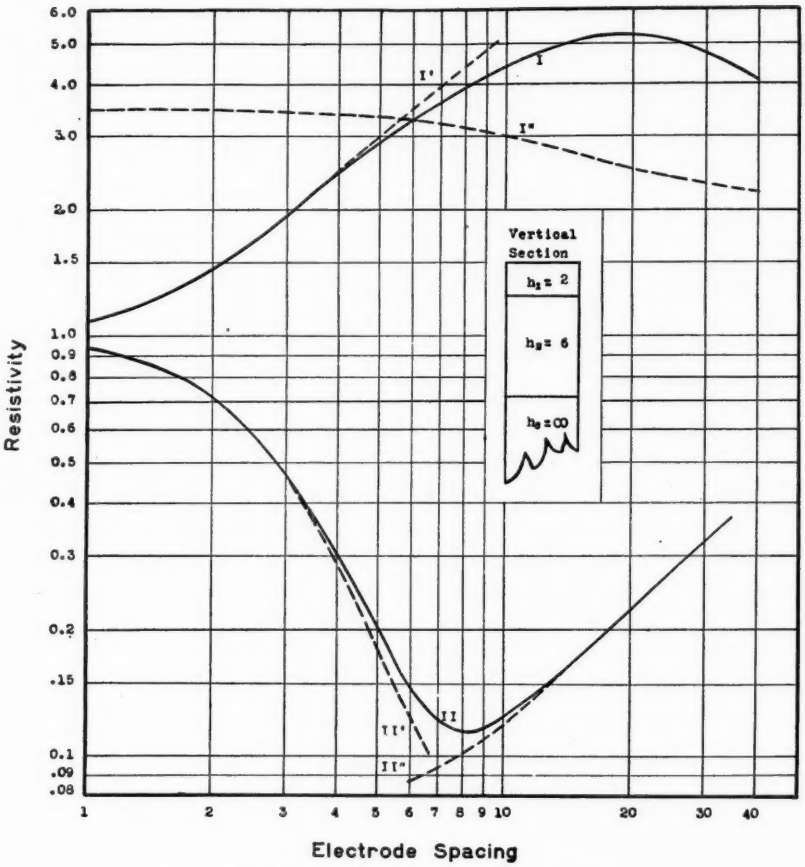


FIG. 8. Three-layer resistivity curves for $\left\{\begin{matrix}\rho_2 = 1/19\rho_1, \text{ or } 19\rho_1;\ \rho_3 = 3\rho_1 \text{ or } 2.11\rho_1 \\ h_2 = 3h_1.\end{matrix}\right\}$.

The final curve shown in Fig. 10 is for a four-layer problem. Its inclusion in the paper is as an example to show the limitations of the extension methods to four-layer problems in which each succeeding bed downward is not large with respect to the one above. In the case presented, a good determination of h_1 is possible. That portion of the

resistivity curve which is supposed to yield (h_1+h_2) and to track with I'' apparently will never join I'' and hence the determination of

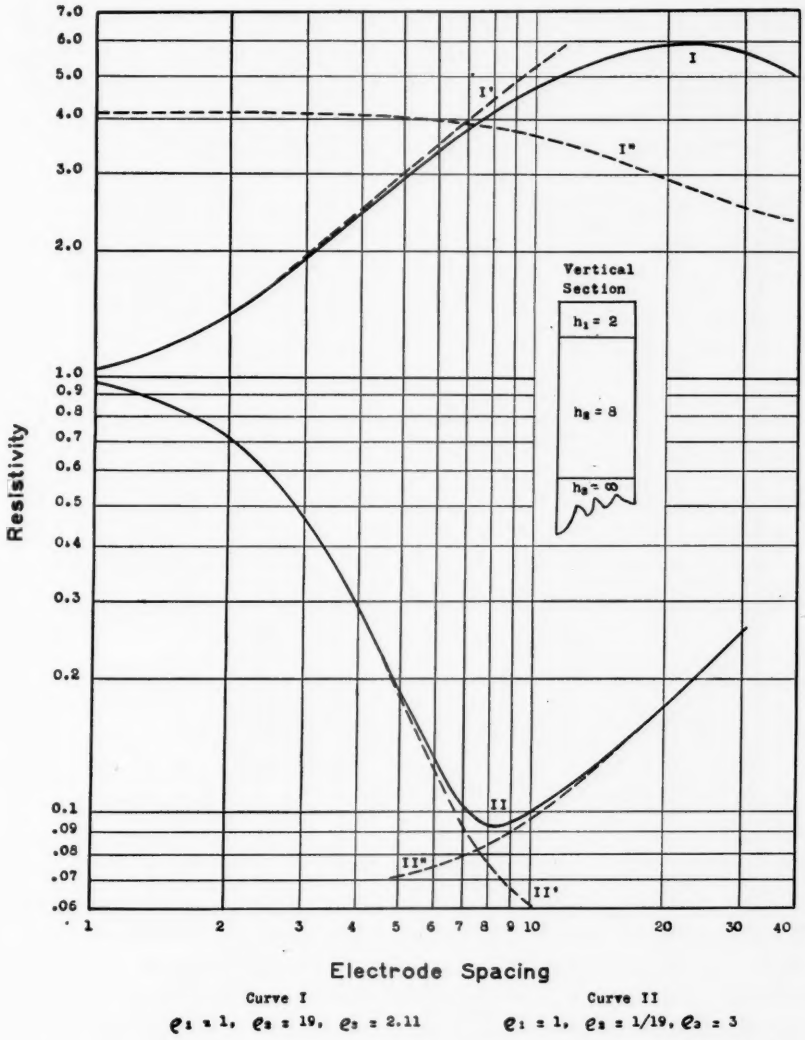


FIG. 9. Three-layer resistivity curves for $\left\{\begin{matrix}\rho_2 = 1/19\rho_1 \text{ or } 19\rho_1;\ \rho_3 = 3\rho_1 \text{ or } 2.11\rho_1 \\ h_2 = 4h_1.\end{matrix}\right\}$.

(h_1+h_2) is impossible. With sufficiently large electrode spacings the thickness of $(h_1+h_2+h_3)$ can be determined, but the values of h_2 and

h_3 are indeterminate with the extension of the methods of Roman and Tagg.

The value of a set of three-layer theoretical curves for various values of h_1, h_2, ρ_1, ρ_2, and ρ_3 is twofold. They are the means of the slower but more powerful interpretation of matching the *whole* field curve against a theoretical curve. They can also be used in conjunction with

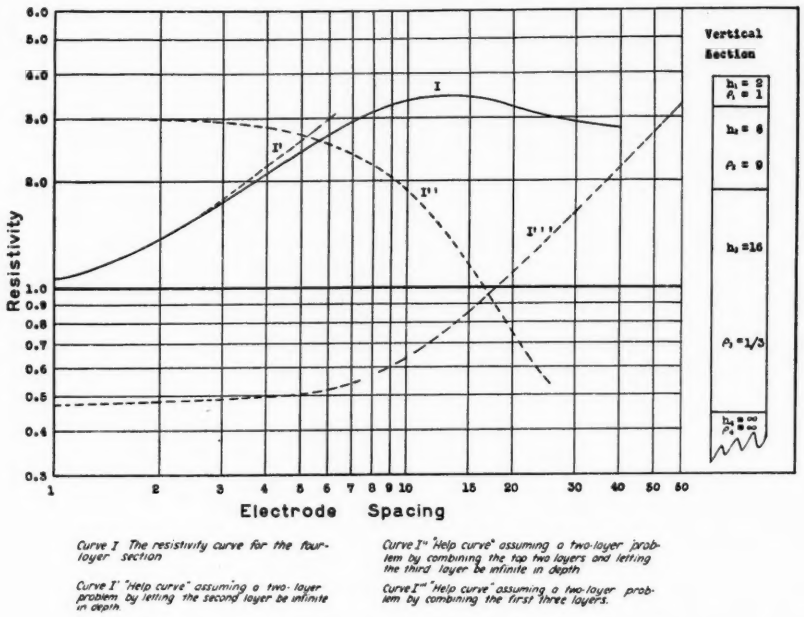

Resistivity
Electrode Spacing
Vertical Section
I
I'
I''
I'''
Curve I. The resistivity curve for the four-layer section
Curve I'. "Help curve" assuming a two-layer problem by letting the second layer be infinite in depth
Curve I''. "Help curve" assuming a two-layer problem by combining the top two layers and letting the third layer be infinite in depth
Curve I'''. "Help curve" assuming a two-layer problem by combining the first three layers.

FIG. 10. Four-layer resistivity and help curves for $\left\{\begin{matrix}\rho_2=9\rho_1;\ \rho_3=1/3\rho_1;\ \rho_4=\infty \\ h_2=3h_1;\ h_3=2(h+h_2)=8h_1\end{matrix}\right\}$.

the extension methods to prevent large interpretation errors due to the effect of anisotropy[10] of horizontal beds or to the effect of inclined beds.[11] Each of these variations from the case of homogeneous horizontal layers may cause changes in the slopes of the resistivity curves sufficient to cause erroneous depth determinations. After a Roman interpretation has been made on a resistivity curve, the theoretical curve closest to the values of k_1, k_2, h_1, and h_2 should be examined to

[10] S. Pirson: Bulletin A.A.P.G. (1935), Vol. 19, No. 1, pp. 37–57.

[11] R. F. Aldredge: Colorado School of Mines Quarterly (1937), Vol. 32, No. 1, pp. 171–186.

find if such a problem can be interpreted with the electrode spacings used in the field.

The method of matching whole field curves with computed curves makes possible the interpretation of the less favorable three-layer problems, and, theoretically at least, problems of four or more layers. For this purpose a large number of theoretical curves are necessary. Computing these from the formulas already developed and published would be a tremendous job unless some mechanical[12] means can be adapted to the work.

[12] The application of the Differential Analyser to these theoretical calculations described by Wetzel and McMurray may prove to be a solution of these difficulties, cf. GEOPHYSICS, Vol. ii, no. 4 (Oct., 1937).

ON THE STRATEGY AND TACTICS OF EXPLORATION FOR PETROLEUM. II*[1]

E. E. ROSAIRE†

ABSTRACT

The need for statistics relative to the cost of finding oil in the ground has been recently stressed by DeGolyer. In the absence of such statistics, it is suggested that the study of outstandingly successful exploration campaigns will permit the deductions of principles which can be used for general guidance.

By showing the parallelism between recent successful exploration campaigns and pertinent illustrations from military history, three of the fundamental Principles of War, relating to the Offensive, to Surprise, and to Security, are found to be applicable to exploration strategy.

In conclusion, the present status of exploration in the Gulf Coast is discussed by analogy to a similar period in 1929 and 1930.

Of late, exploration for petroleum has received enough formal recognition so that it is now classified as one of the major divisions of the industry, taking its place along with production, transportation, refining and marketing. From the bearish tone of recent papers on the subject, there is more than a little suggestion that this recognition barely escapes being a posthumous reward, for great pessimism is expressed as to the petroleum which will be required ten or fifteen years from now, and which should, apparently, be found today.

Now, if that pessimism is justified, then this business of exploration becomes a serious thing, for, obviously, the oil to be used in our 1948 model cars will probably be made up to an appreciable extent by the oil discovered between now and then. But, another assumption has to be made, and that is, that the cost of marketable petroleum products at the corner filling stations must be less than the cost of an equivalent and different power source under competitive marketing conditions.

Cost analyses for four primary divisions of the industry, i.e., marketing, refining, transportation and production, are available in exhaustive form, and have led to materially improved practices and technique. But, what *does* it cost to locate an untapped source of petroleum?

In a recent paper, DeGolyer[2] has raised this question. Even in the

* Paper read at Fall Meeting, Nov. 19, 1937, Houston, Texas.

[1] Cf. Journal of the Society of Petroleum Geophysicists, Vol. 6, No. 1 (July, 1935).

† Subterrex, Houston, Texas.

[2] Future of Petroleum Exploration in United States. E. DeGolyer, Bulletin of the American Association of Petroleum Geologists, Vol. 21, No. 6, June 1937, pp. 706–714.

absence of a proper analysis of collected and, what is more to be regretted, probably unavailable data, the general answer is obvious, and will be to the effect that the cost of discovering reserves is much like the very young lady,

> " . . . who had a little curl
> Right in the middle of her forehead.
> When she was good she was very, very, good,
> And when she was bad she was horrid."

If our resources are exhaustible, as they certainly are, and if, as Pratt[3] points out, the discovery rate is declining critically, then this cost finding is certain to become of material importance. Further, if after a half century of exploration the results range from excellent (profitable) to poor (unprofitable), then exploration is an art, rather than a science like chemistry or physics, and all that can be hoped for is a development of principles, or general rules, which possibly may be used for guidance rather than control.

The same, of course, is true of business, of politics, and of war. In my reading I have found "Get Rich Quick" schemes which usually ended the proponent in jail; copybook maxims justified by the success of Horatio Alger heroes, but no fundamental principle except to "buy low and sell high." I have found no convincing Primer of Politics. I have found, however, that the Art of War has been a source of interest to historians and students for years, and, as a result of their intensive study, certain principles have been recognized as having played important parts in the successes of the Great Captains of War.

For some time I have been making a study of the possibility that a translation of these principles could be made into a form applicable to the field of exploration for petroleum. As this study progresses, there appears more and more similarity between many cases of discovery at a premium and decisive military campaigns, and also between poor generalship and dismally unsuccessful exploration campaigns. And of course, a discovery at a premium is simply a case of very low finding costs. The reason is that in war, as in exploration, the relation of the cost to the profit has rarely been figured, so that many wars, though won, are not worth the winning, as witness the last. So, in exploration, the cost of acquiring oil in the ground has rarely been related to the resultant profit, as DeGolyer points out. It is not unreasonable, then, to seek out the principles

[3] Discovery Rates in Oil Finding. W. E. Pratt, Bulletin of the American Association of Petroleum Geologists, Vol. 21, No. 6, June 1937, pp. 697–705.

which played important parts in the winning of decisive wars, and determine whether analogous principles hold in obviously successful exploration campaigns.

Not all wars produce Great Captains, for too often only Pyrrhic victories result, wherein the losses of victor and vanquished are of the same order of magnitude. Such wars may be compared to the steps taken to increase the volume of gasoline sales by putting in the fourth filling station on the only unoccupied corner, whereby the sales department loses more money so that the production and transportation departments can show greater profits.

It is interesting to note that certain battlegrounds appear time and again as important theatres of war, as in the cases of Belgium and Armageddon, but, naturally, under widely varying attendant circumstances. Similarly, certain sedimentary basins of the United States have been characterized by successive periods of exploration for petroleum deposits. The Gulf Coast has been the scene of intensive exploration for petroleum deposits on three recognized occasions, the first from 1900 to 1905, when natural surface expressions of structure were the means of discovery, in the way of drilling on topographic highs, topographic lows, paraffin dirt beds, or gas seeps. Then a generation later, two simultaneous campaigns were launched, the torsion balance being active from 1923 to 1928, and the refraction seismograph from 1924 to 1929. Most recent of all was the intensive use of the reflection seismograph from 1933 to the present time, when the areas previously explored by the earlier methods in exhaustive fashion were again explored even more intensively.

If Principles of Exploration exist which are as fundamental as the Principles of War, then they should have been as applicable in the Gulf Coast a generation ago, when prospectors were fishermen because of the chance to find gas seeps thereby, as they are applicable today, when fishermen object to prospectors because of the fear of water pollution following anticipated development.

Certain adjustments in viewpoint are required in drawing a parallel between war and exploration. Thus, in war, the object is to defeat an enemy with due consideration to existing natural conditions; in exploration, the object is to win an oil field from nature with due consideration to existing competition. As in the case of the recent Italo-Abyssinian campaign, the enemy may be one which could be defeated readily were it not for difficult terrain, while a program of geophysical exploration would be easier if forty year concessions were in force, as

in Venezuela, rather than the existing, unbridled, competition characterisitic of the Gulf Coast.

A hostile resistance is active, replying to pressure with pressure. The resistance of nature is inanimate, passive, yet quite as important. If hostile resistance yields slightly at a given point, additional pressure of an appropriate form may effect a breach or a break through; so, if, as a result of exploration, a marginal anomaly is found, additional effort with a method of higher finding power may win the desired result.

Since the basic problems in war and exploration are so similar, then it may be of interest to examine the applicability to exploration of the Principles of War, which have been recognized as fundamental in military strategy.

Of these latter it is said, "The principles of war are not numerous. Any schoolboy can learn them by heart in a few minutes, but a whole lifetime can be spent in the study of their application in war without exhausting the possibilities of the art."[4] Herein lies the justification for case treatment (which, unfortunately, appears so rarely in exploration literature), in making available for study incidents outside the individual's experience. Consider Napoleon's LXXVIII Maxim, "Read and re-read the campaigns of Alexander, Hannibal, Caesar, Gustavus, Turenne, Eugene, and Frederick; model yourself upon them; this is the only way to become a great captain and to discover the secrets of the art of war. Your genius, enlightened by this study, will reject the maxims opposed to those of these great men."[5]

I propose to quote, from the Training Regulations of the U. S. Army, three of these Principles, those dealing with the Offensive, with Surprise, and with Security, and, drawing upon military history for illustrative examples of their application, to show by analogous and appropriate situations that these same Principles are also of fundamental importance in the art of exploration.

I. THE PRINCIPLE OF THE OFFENSIVE

From the Training Regulations of the U. S. Army, "Offensive action is the only means by which a decision is gained. When successful, the offensive brings victory, while the defensive can only avoid defeat. The only effective way to wage war is to act on the offensive for the

[4] If War Comes. R. E. Dupuy and G. E. Eliot, Macmillan, 1937, p. 27.

[5] World's Military History. W. A. Mitchell, Military Service Publishing Company, 1931, p. 737.

purpose of delivering a main blow in a decisive direction. . . . The offensive increases the effectiveness of a force adopting it, as it raises morale, permits concentration of effort, and allows freedom of action. The defensive should be assumed only to assist offensive action elsewhere, to gain time, or to utilize advantages of terrain, so as to compensate for weakness. Although the offensive confers great advantages, these advantages can be utilized only when the means available are sufficient to provide reasonable chances for success."

Thus, on the Chinese mainland at present, Japan has seized and held the initiative, and thereby forced China to the Strategical Defensive, whereby China can only hope to avoid defeat. In the Civil War, after Gettysburg, Lee was on the Strategical Defensive, and though he won battle after battle, only could try to postpone inevitable surrender, hoping meanwhile for European interference. In Spain, the Loyalists have been forced to the Strategical Defensive, and can try only to avoid defeat, hoping that France, England and Russia can effect favorable intervention.

Not long ago, during the period when oil was selling at materially less than a dollar per barrel, reference was made to one company still listing among its reserves in storage some Ranger crude which had been bought at the peak price of $3.00 per barrel. The discovery of Ranger caught that purchaser on the Strategical Defensive, and is a case where the hope of avoiding defeat was not realized.

An interesting case is that presented by the local Houston natural gas companies, with big investments in pipe lines to the large and apparently quite satisfactory reserves in South Texas. Now that Humble has located large natural gas reserves near Houston, and is skimming the cream off the local industrial market, these natural gas companies are paying the penalty for years of remaining on the Strategical Defensive, and may well realize the appropriateness of Napoleon's XIX Maxim, that "the change from the defensive to the offensive is one of the most delicate operations in war."[6]

Quoting from the Principle of the Offensive, (above), "Although the offensive confers great advantages, these advantages can be utilized only when the means available are sufficient to provide reasonable chances for success."

As military examples of offensives launched when the means available did not provide a reasonable chance for success, consider Lee's

[6] World's Military History. W. A. Mitchell, Military Service Publishing Company, 1931, p. 732.

use of Pickett's troops at Gettysburg (the high tide of the Confederacy); the fruitless German offensives before Verdun, or the Gallipoli Expedition.

As exploration examples, contrast the two refraction campaigns launched in the Gulf Coast by the Amerada, the first in 1929–1930, the second 1935–1936.

The first venture was made jointly with the Rycade, and was based upon the expectation that the use of ten- and twelve-mile shot lines would lead to the discovery of additional salt domes in those areas which had been explored intensively by that same method. The only concrete result was the discovery of the East Stratton Ridge salt dome, where caprock and salt were found to exist at a depth so shallow that the technique of 1926 or 1927 would have resulted in discovery.

The second venture was made in 1935–1936, jointly with the Louisiana Land and Exploration Company, and was projected on the premise that, since the only maps available for Southeast Louisiana in the earlier (1927–1929) refraction campaign were very inaccurate, a possibility still existed of discovering marginal refraction anomalies which could then be evaluated by reflections. The correctness of this premise has been indicated by the discovery of two oil fields (Raceland and Des Allemands) by these combined tactics.

Another illustration of adequate offensive preparation, which parallels the Amerada-Louisiana Land and Exploration Company campaign described above, was the Stanolind's use of combined tactics in the Gulf Coast from 1933 to 1936. By the use of reflections to evaluate marginal gravity anomalies, the discoveries of Hastings, South Houston, Turtle Bay, and Clinton followed in quick succession in an area which had been subjected already to intensive exploration.

II. THE PRINCIPLE OF SURPRISE

From the Training Regulations of the U. S. Army, "Surprise in some form is essential in order to obtain the maximum effect with the minimum loss. It may take the form of time, place, direction, force, tactics or weapons. Secrecy, rapidity and preparation are the main factors."

As illustrations of the effective utilization of surprise with adequate preparation, the following military incidents will serve.

In 204 B. C. Scipio landed in Africa, with the reduction of Carthage as a general objective, and encamped near the Carthaginian town

of Utica. Faced by a potential union of three enemy units, he decoyed one into an impossible position, and destroyed it. The other two units, encamped separately nearby, were thoroughly investigated during the time required for decoy negotiations. Finally, Scipio attacked and destroyed these units. This attack was made suddenly, at night, and Scipio also fired the enemy huts to complete the panic, having previously observed their congested and vulnerable locations. "Many of the enemy perished in their huts while half asleep, many were trampled to death in the exits, while those who escaped the flames were cut down unawares by the Numidians posted at the gates of the camp. . . . Meanwhile, the Carthaginian soldiers, aroused by the fire, rushed out of their own camp. This was as Scipio had hoped and anticipated, and he at once fell on the rabble. Instantly he followed this up by launching his attack on the gates of the (Carthaginian) camp, which were unguarded as a result of the confusion. It is reported that some forty thousand men were either slain or destroyed by the flames, and about five thousand were captured."[7] Scipio's losses were inconsiderable.

In 1847, Winfield Scott, en route to his duplication of Cortes' feat of conquering Mexico City, was confronted by Santa Anna, who was encamped on the supposedly impregnable heights of Cerro Gordo. During the night, Robert E. Lee, then a captain of engineers, was able to have some small howitzers man-handled to a commanding position unguarded by the Mexicans, whereby the assault of Scott's troops was covered, Santa Anna defeated, and Mexico City, later, captured.[8]

To the military principle of surprise, there is a civil analogy in novelty, or originality. Some outstanding examples of these may well be considered.

Henry Ford achieved an industrial surprise and financial success by applying mass production to the automobile with the idea of utilizing the resulting lower cost per unit to reach a greater volume of sales. He achieved these with his Model T, which eventually sold for less than $400.00.

A case of successful surprise in exploration was the introduction of the reflection method into the contract field by the Geophysical Service, Inc., in 1930; a case of surprise in time, place and methods. Although at least fifteen competitors subsequently entered that same

[7] A Greater than Napoleon, Scipio Africanus. Liddell Hart. Little, Brown and Company, 1927, p. 135.

[8] Old Fuss and Feathers. A. D. Howden Smith, Greystone Press, 1937, pp. 280–284.

field, not one has approached the size and financial success achieved by the Geophysical Service, Inc.

A recent survey by Fortune, as to the man-in-the-street's idea of the employer who has done most for his men, showed Ford far in the lead. This is undoubtedly the effect of his 1921 announcement of a minimum daily wage of $5.00, which was a psychological surprise. Consider the cost of present day advertising required to establish a similar impression in the mind of the public for a competitor of Ford.

On the battlefield, a rather frequent accompaniment of a successful surprise, in fact one of the hoped for results, is the demoralization of the enemy. Illustrations are the effect of Scipio's night attack on the Carthaginians at Utica, and in the World War, the effect of gas at Ypres, and of tanks at Cambrai. An analogous effect in exploration was the demoralization of the entire oil industry as a result of the discovery of the East Texas Field.

There are numerous examples of surprise in the field of exploration, effected by the introduction of novelty in methods, tactics, time, and place.

Of the effect of new methods, reference need only be made to the Gulf's early use of refractions in the Gulf Coast from 1924 to 1928; the combination of radio time-break, electrically-recording seismographs, and distance determination by air wave, which enabled the Geophysical Research Corporation to replace the Seismos in the contract refraction field in 1927. Still another example was the Amerada's successful introduction of reflections into the Mid-Continent in 1927.

The surprise mentioned above, effected by the Geophysical Research Corporation in the refraction field through originality in field methods, made possible the most spectacular exploration campaign witnessed to date, the Louisiana Land and Exploration Company's refraction campaign in the lakes and bays of South Louisiana in 1927–1928, when eleven salt domes were found in nine months. For the basic novelty, Colonel E. F. Simms was primarily responsible, who about 1920 decided that salt domes could exist under water as well as under land, and secured the state leases under which most of these new domes were later found. The initial attempts to exploit his basic originality were failures, for several dry holes were drilled on these water leases just prior to the successful refraction campaign. Here, the full surprise effect was only realized by the combination of novelty in tactics and place in the use of an old method in a new area.

Another example of surprise, resulting in discovery at a premium, was demonstrated in the practically simultaneous projection of two independent campaigns in the Illinois Basin in 1935 and 1936, one by the Pure Oil Company, the other by a joint venture of the Adams Louisiana Company and the Felmont Corporation. Both campaigns were based on novelty (the application of an old method to a new area), in searching with reflections for structures beyond the reach of the core drilling used in the earlier exploration campaigns.

In military history, there are cases of record where complete surprise was achieved, but, due to inadequate offensive preparations, the resulting opportunities were not properly exploited. One case was in 1864, when the Federal troops exploded a subterranean mine under the defenses of Petersburg; of more recent vintage were the initial use of gas by the Germans at Ypres in 1915, and the initial use of tanks by the British at Cambrai in 1917. In each case complete demoralization of the enemy resulted, together with a nearly complete collapse of the defenses at the point attacked. Yet in no case was the opportunity exploited.

As examples of achieved but unexploited surprise in exploration, the following illustrations will serve.

In 1931, an exploration campaign was initiated in Nueces County, Texas, using the combined tactics of reflection following a gravity survey. The discovery wells at the King and Stratton gas fields confirmed two of the predictions of structure which followed. Shortly thereafter the campaign was abandoned, but, subsequently, at least eight additional oil fields have been discovered in that county, some of which confirm the geophysical predictions made in that early campaign.

Again, in 1931, the discovery of oil at the Iowa and Manvel fields proved the value of the "Iowa" type of reflection dip highs. Yet, the two companies, for whom that early reflection work was done, were not among those present in the really big payoffs at Anahuac, Hastings and Friendswood, for neither company made any serious effort in 1931 to exploit further the exploration method then new to the area.

III. THE PRINCIPLE OF SECURITY

From the Training Regulations of the U. S. Army: "Security embraces all measures taken to guard against observation and surprise, to insure against hostile interference with operations, and to gain and maintain the power of free action."

Obviously, the Principle of Security is implied in the Principle of Surprise, for only by complete security can the full fruits of surprise be gained. With reference to guarding against hostile enterprise, the outstanding example of the violation of this principle was in the failure of the Geophysical Research Corporation to secure adequate patent protection while developing the refraction and reflection techniques, whereby competitors not only were allowed to enter and crowd the field, but in addition, that company was faced with embarrassment and possible financial loss in the form of an adverse patent suit actually filed and finally settled out of court.

An illustration of the "hostile interference" resulting from violation of the Principle of Security may be found in the recent north extension of the Anahuac oil field by an independent operator, to the confusion of the major company which had discovered the prospect geophysically. And it is interesting to notice that inadequate security was indicated a second time in the spectacular but extremely costly lease campaign launched by that same company after coring the oil sand in the discovery well at Friendswood a few months ago.

CONCLUSION

IV. THE PRESENT SITUATION

For a critical estimate of the present situation in the Gulf Coast, attention is called to similar situations which existed in the recent past.

From 1900 to about 1905, Gulf Coast exploration was based upon surface evidence of buried structure, such as topographic anomalies, gas seeps, and paraffin dirt beds. During the period 1901 to 1905, the average discovery rate was slightly more than two oil fields per year. Outstanding among these discoveries were Spindletop, Humble and Jennings.

Yet, about 1924, Mr. Henniger[9] said, "That it becomes increasingly difficult to find additional domes is apparent when we consider that of the forty known domes in the Gulf Coast, thirty-seven were found from 1901 to 1913. Of the other three, two were found in 1917 and one in 1922. Since the discovery in 1917 of the Section 28 dome . . . approximately 675 wildcat wells have been drilled in search of new domes on the coast, involving an expense estimated at $20,000,000,

[9] Geology of Salt Dome Oil Fields. DeGolyer and Others, American Association of Petroleum Geologists, 1926, p. 776.

exclusive of the cost of leases and overhead expenses. Yet only one new dome has been found during this period and it has not yet proved profitable commercially as a source of oil." From this, the cost of discovery for one dome was indicated to have been $20,000,000.00.

From 1924 to 1929, the refraction seismograph dominated exploration in the Gulf Coast. To appreciate this, one has only to recall the year 1924–1925, when five shallow domes were found by the Seismos, G.m.b.H. for the Gulf (Orchard, Fannette, Hawkinsville, Starks, Fausse Point), the East Texas campaign following the first indication of oil at the Boggy Creek salt dome, where one deep and several shallow domes were found during 1927 and 1928; and the Louisiana Land and Exploration Company refraction campaign over the bays and lakes of South Louisiana, whereby eleven salt domes were discovered in nine months, at a cost of less than $50,000.00 each. In spite of such successful performance, the continued intensive use of the method resulted in a series of dry holes during 1929, 1930 and 1931.

Those of us who were actively in the refraction field at the time did not take these diminishing returns in a lackadaisical fashion. In vain attempts to increase materially the finding power of the methods, the distances between shot and recorders were increased to ten and even twelve miles, lower period seismographs were introduced, graphical methods (the old red and green charts) were required to display the smaller anomalous times, charges were buried to depths of two hundred and fifty feet, and the use of the air wave for distance determination was discarded in favor of transit and chain. To our continued bewilderment, no re-vivification of the method followed, for no material improvement in finding power had been achieved. Finally, the low price of oil resulting from the discovery of the East Texas field rang down the curtain on the remaining amount of ineffective refraction exploration.

The last gallant but futile attempts to increase the finding power of the method yielded only marginal anomalies, of which the Iowa oil field was one, Turtle Bay another, and St. Martinville a third. These, and other contemporary marginal anomalies, were vaguely believed to have some economic importance, but no one then had any logical or reasonable approach to an evaluation of the potentialities, short of the blind gamble of drilling wells.

The reflection method had been introduced in 1929, and late that year the use of dip determinations was discovered, yielding a subsurface, "Iowa" type, high at the Darrow Dome. No strong support was

given to the further use of the method, although in 1931, the method was used to show a dip high at Iowa, and at Manvel, prior to development. Without honor in our own province, we proponents of the reflection method had to wait for the arrival here of immigrant Oklahoma operators, already convinced of the efficacy of reflection methods by the work of the Geophysical Research Corporation in Oklahoma, and then, and then only, did the method come into general use.

From 1932 to the present time, the reflection method has dominated the Gulf Coast. Again we see the discovery cycle taking place, for early in this period was done the reflection exploration which led to the discoveries of oil at Anahuac, Hastings, LaFitte, and Friendswood. Of late, however, the prospects found are marginal, and the number of dry holes is increasing. Strenuous efforts are being made to increase the finding power by means of volume controls, deeper shot holes, continuous profiling, and scrambling by sound tracking, whereby the computors speak with certainty of faults with fifty feet of throw, but remain in blissful ignorance of those with five hundred feet of throw. Again, the mountains labor, and bring forth mice.

For the third time the cycle has been completed, the periods of high discovery rates and low finding costs of 1900–1905, of 1924–1928, and of 1932–1934, have each been followed by the complementary periods of low discovery rates and high finding costs from 1906–1924, from 1929–1932, and 1935 to 1937. Or, the cycle could be described more optimistically, i.e., that each period of low discovery rates has been followed by a period of high discovery rates, coincident with the introduction of surprise in the form of a new, and effective, method of exploration.

Why do weapons have potentialities at first which they do not, of themselves, display later? Why was the use of gas, or of tanks, never again so outstandingly successful as in the first trials, being considered now relative disappointments in Spain and China? Because, after the initial use, the law of diminishing returns starts to operate against surprise, for no one weapon has ever long dominated the battlefield. The answer for the torpedo boat was the destroyer; for the torpedo, water tight compartments and blisters; for the submarine, the depth charge, the mine barrage, and the convoy system; for the machine gun, the tank; for the tank, the anti-tank gun. With the appearance of the answer, the possibility of surprise vanishes.

The use of still new weapons never resulted again in the same amount of surprise when used subsequently against opponents with

modern armaments, but, in Abyssinia, surprise, in time and place, again achieved a similar demoralizing effect, the case of an old method in a new area.

Why do these exploration methods, which initially display promise of exploration at a premium, eventually lose the Midas touch? As was mentioned earlier, the Principles of War apply to beating an opponent in the face of terrain and weather, while in exploration, similar Principles apply to winning a resource from nature, in the face of competition. In the case of favorable structures, only a finite number exist, and when those have been found, there are no more apples left in the barrel. Nature's passive defense against a successful exploration method is exhaustion, for success increases the hazard of further exploration. So, after the initial use of reflections in Oklahoma, opportunities for discovery at a premium there never appeared again, but were present in the early use of the same method in new theatres of exploration, as in the Gulf Coast, and again, in Illinois.

Now, what is required of an exploration method before its use in any province is justified under existing conditions? First, the method must be capable of displaying an anomaly which will be an important clue to the objective, i.e., the type of structure sought. Second, the anomaly displayed should be at least ten times the observational error i.e., the magnitude of the anomaly must not be marginal, for otherwise no advantage can be anticipated over existing methods. With such a method, and with the past and future assistance of known methods, another opportunity for discovery at a premium may be at hand, even in the intensively explored Gulf Coast areas.

What can be expected for 1938, and after? As it happens, the probable objective for the next exploration campaign, which will cover the Gulf Coast once again, is the type of structure already producing oil in several cases, at Tepetate, Hardin, Bay City, Aldine and Hamman. And while these examples may not display the promise expected of major fields, neither did Raccoon Bend predict a Conroe, nor did Iowa and Manvel forecast the payoffs at Anahuac, Hastings and Friendswood. What *could* be the value of a Tepetate type of structure under the most favorable conditions of sand deposition?

Where reflection correlations are favorable, such structures have been found, while suggestions of many similar structures have been indicated by still unexplained gravity anomalies, and by marginal reflection anomalies in the way of misclosures (from dip traverses), unclosed noses, and anomalous dips. This type of structure requires faulting for closure, and the approach which now seems favorable

lies in the detection of the faulting apparently responsible for accumulation. As more and more "grass root" electrical logs become available and receive proper study, the evidence strongly points to the possibility that this faulting has reached to surprisingly shallow depths, and can be located at or near the surface by suitable exploration methods other than, but of course not excluding, the drill. In view of these existing circumstances, it is reasonable to suppose that, just as in 1932, the Gulf Coast will again suffer intensive exploration for a type of structure known to accumulate oil in specific cases.

The early campaigns using the refraction, or reflection, method, succeeded because of surprise, or novelty; subsequent campaigns, in these same provinces, with the same tactics even more highly developed, were less decisive, or failed, because surprise, i.e., originality, no longer was present. The early, low cost, success increased the hazard of further exploration.

Once reflections had been secured, and the apparatus requirements recognized, improvements in the method followed as a natural consequence. On the other hand, the finding of one Conroe seems to have eliminated the possibility of finding another. The continued use of an exploration method results in improved data through a reduction in the magnitude of the observational errors, and, simultaneously, results in an increased hazard through a reduction in the existing anomalies with effects greater than these observational errors.

Prospectors might be likened to winter wanderers who come upon a summer resort closed for the season. In the bowling alleys, they find the pins set up, though the pin boys, of course, are absent. Obviously, even the early tyro with a primitive technique, susceptible to great improvement, has an infinitely greater chance for a higher score than the tardy master bowler whose perfected technique is of no avail after all the pins have been knocked down.

In the words of the Principles of War, "Surprise in some form is essential in order to obtain the maximum effect with minimum loss." Within our limited field, it may well be said that "Originality is in some form essential in order to obtain discovery at a premium," or more simply, "The early bird catches the worm."

APPENDIX I

THE TWO GENERAL STAGES OF FINDING POWER

Two stages can be recognized generally in the use of successful exploration methods.

If introduced at a time when undiscovered anomalies exist which

have effects several times greater than the observational error of the method, then the method may be considered as decisive in that the opportunity for surprise exists, and so discovery at a premium is possible. For a given method, this period might be called the primary, or "decisive" stage.

After the outstanding anomalies have been discovered, the remaining anomalies, if any, are comparable with the observational error of the method, and only diminishing returns can be expected. The opportunity for surprise on a grand scale no longer exists, although on a minor, or local scale, surprise can still take place. The method then takes position along with the earlier used methods, and a combination of "indecisive" methods must then be relied upon for discovery, each contributing somewhat comparable assistance. This period might well be called the secondary, or "indecisive" stage for the method in question.

In the use of a method, both stages may be present, or the first stage may be absent. The "decisive" stage was, in general, absent in the case of aerial photography, for surface geological methods of exploration, by comparison the hard way, had made available the pertinent information on the surface evidence of subsurface folding. Consequently, the contributions of aerial geology were, in general, indecisive, a tribute to the thoroughness of the surface geologists.

The discovery claims made for a method in the "decisive" stage frequently call forth disparaging comments to the effect that sufficient credit has not been given to the contributions made by earlier methods, though, admittedly, these were "indecisive."

Thus, "It is true that in many areas where the geologist has set up the essential, preliminary, geological, background, the geophysicist has appeared to reap all the glory by presenting evidence of localized structure . . ."[10] Also, many shallow salt domes discovered by the refraction method were recognized as known but marginal (or "indecisive") surface prospects, and several "Iowa" type reflection structures were discovered by reflection dip details of marginal (or "indecisive") gravity anomalies. This practice of claiming full credit for one method is annoying, to say the least, to those investigators who feel that their earlier, "indecisive," contributions are not properly recognized.

A similar situation has been observed very frequently in patent

[10] Geology and Geophysics. O. L. Brace, Bulletin of the American Association of Petroleum Geologists, February, 1937, Vol. 21, No. 2, p. 210.

law, and the Gordian Knot has been cut by the Courts in their postulation and acceptance of the "Last Step" rule, which is to the effect that the one who brings success out of failure is the inventor. This rule was enunciated by the U. S. Supreme Court in the barbed wire patent case in 1891, in which the earlier invention of a diamond shaped prong strung on wire was held subordinate to the later invention of barbed wire as we know it now. The Court said, in part, "But it is plain from the evidence, and from the very fact that it was not sooner adopted and used, that it (this last step) did not, for years, occur in this light to even the most skilled persons. It may have been under their very eyes, they may almost be said to have stumbled over it; but they certainly failed to see it, to estimate its value, and to bring it into notice. . . . Now that it has succeeded, it may seem very plain to anyone that he could have done it as well. This is often the case with inventions of the greatest merit. . . ."

To the writer this quotation seems most applicable to the clarification following the application of an exploration method, in the decisive stage, to a prospect recognized as marginal by one or more methods, in the indecisive stage. (Vide Anahuac, decisively indicated by reflections, though earlier indicated indecisively by refractions and gravity surveys, etc.) The "Last Step" rule is the justification for the common practice of giving credit to the discoveries resulting from the use of a method while in the "decisive" stage. When, however, only diminishing or "indecisive" returns are yielded by the use of a method, then discovery at a premium can no longer be expected to result by the use of that method alone.

APPENDIX II

MAJOR TACTICS

If we consider geophysical methods as Minor Tactics, then the five broad classes of exploration methods, as used by Pratt,[11] constitute Grand Tactics, namely (1) random drilling, (2) obvious surface evidence, (3) geology, (4) geophysics and (5) deeper drilling. In Fig. 1, the discovery data for the first four of these methods, and the total for all methods are shown, using running ten-year averages instead of the successive five-year averages used by Pratt.

For the first three of these methods (random drilling, surface evidence, and geology) these averages indicate a generally increasing

[11] Discovery Rates on Oil Finding. W. E. Pratt, Bulletin of the American Association of Petroleum Geologists, Vol. 21, No. 6, June 1937, pp. 697–705.

success, attending the use of the method, until a peak is reached, with a consequent drop off from the maximum. During the period when increasing or constant success followed the use of the method, that method can be said to have been, more or less, in the decisive stage. After the peak has passed, however, the method can well be considered as being in the indecisive stage, where the chance of success will be materially increased by the use of that method in combination with others.

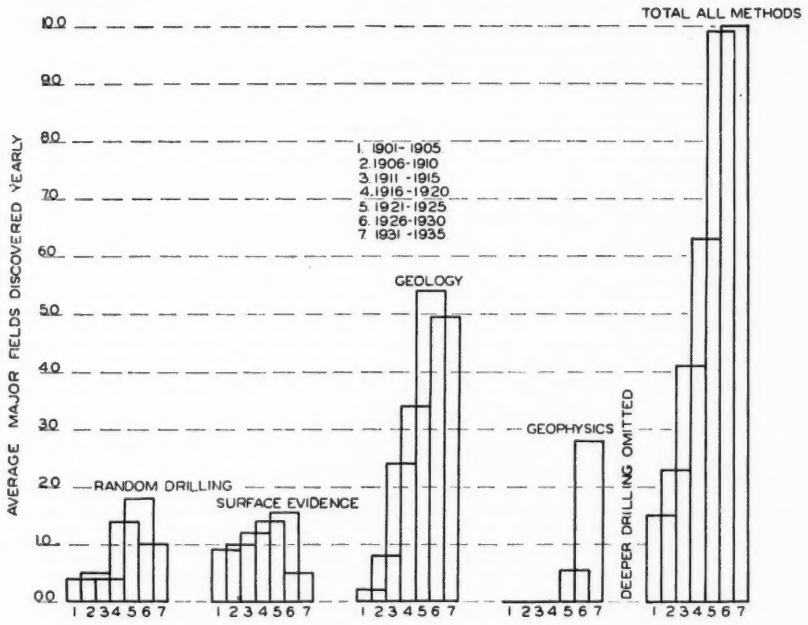


FIG. 1

To date, geophysical methods of exploration are showing an increasing successfulness, and so, as yet, geophysical exploration can be considered as being in the decisive stage. And, further, since the successfulness of the earlier used methods is falling off, it is obvious that geophysical methods of exploration will probably be required to shoulder an increasing burden if the overall discoveries are not to show a decrease.

This requirement is imposed upon geophysics at a time when two important geophysical methods (gravity and refractions) are definitely out of the decisive stage, and when another geophysical method,

to date the most promising of all[12] has passed out of the decisive stage in the Mid-Continent, and is rapidly approaching, if not already in, the indecisive stage in the Gulf Coast.

Geophysical exploration must remain in the decisive stage in order to shoulder the indicated burden. The situation calls for originality, or surprise, in one or a combination of the three fundamentals of an exploration campaign, which are (A), the theatre of operations, (B), the objective, and (C), the method.

As an illustration of adequate originality in the strategical approach (A), the recent reflection campaigns in Illinois have been cited. Other illustrations are the Salt Dome Oil Company's use of the torsion balance on the waters of Galveston Bay, and the reflection exploration which resulted in the Superior-Pure "wildcatfish" in the Gulf waters off Cameron Parish, Louisiana.

As an illustration of adequate originality in the strategical approach (B), the "Tepetate" type structure in the Gulf Coast has already been cited, while the recent discoveries in the San Joaquin Valley in California may constitute another example.

A possibility of adequate originality in the strategical approach (C), may be in the use of the Electrical Transient method of prospecting now under investigation, and with interesting results indicated to date.[13]

Another possibility of adequate originality in the strategical approach (C), lies in the geochemical method suggested by the early work of Laubmeyer,[14] continued by Sokolov[15] and his associates in Russia, and now under investigation in the United States. With the reduction of this geochemical method of exploration to field practice, an interesting combination of strategies (A), (B), and (C) is possible, for the new (to geophysics) and most promising objective of stratigraphic prospecting[16] should then be attainable.

[12] But then, any method in the decisive stage always seems the most promising of all. Author.

[13] Electrical Transients in Geophysical Prospecting. Louis Statham, GEOPHYSICS, June 1936, Vol. 1, No. 2, pp. 271–277.

[14] A New Geophysical Prospecting Method, Especially for Deposits of Hydrocarbons. Dr. G. Laubmeyer, Petroleum, Vol. 29 (1933), No. 18, pp. 1–4.

[15] Summary of the Experimental Work on Gas Survey. V. A. Sokolov, Moscow, Neftyanoye Khozyaystvo, Vol. 27, 1935, No. 5, pp. 28–34.

Methods of Interpretation of Gas Survey. V. A. Sokolov, Moscow, 1936.

[16] Stratigraphic Versus Structural Accumulation. A. I. Levorsen, Bulletin of the American Association of Petroleum Geologists. Vol. 20, No. 5, May, 1936, pp. 521–530.

MEASUREMENT OF RELATIVE GROUND MOTION IN REFLECTION RECORDING*

D. H. GARDNER†

ABSTRACT

A description of the method employed in determining the relative sensitivity of a reflection seismograph to harmonic displacement of 10^{-3} inches is given. Results of comparing the sensitivity obtained at this level to the sensitivity used in reflection recording show a ground motion of 10^{-8} inches for the deeper reflections. Comparisons are made between the sensitivities of the reflection seismograph and a mechanical seismograph taken at a level of 10^{-5} inches.

INTRODUCTION

The amplitude of motion of the earth's surface at the seismopickup location during the arrival of reflected waves is influenced by a number of variables. Among these, the size, location and efficiency of the dynamite charge, the nature of the media of the wave paths, the depth of the reflecting interfaces and the surface conditions at the seismopickup location play an important part. When these factors are ideal, small dynamite charges and low sensitivity levels of the recording apparatus are adequate for recording the reflections; when adverse, larger charges and high sensitivity levels are demanded. However, both the dynamite charges and the sensitivity level have their practical limits of application.

Due to the friction of the wind on the surface of the ground and its effect on nearby objects, the vibrations from traffic and heavy machinery, and the disturbances transmitted through the atmosphere a threshold of ground unrest exists even after filtering out the lower frequency microseisms.

When recording the deeper reflections the sensitivity is usually adjusted to this threshold of unrest. In order to determine the magnitude of this unrest and that of the deeper reflections, the following method of measurement was used.

METHOD OF MEASUREMENT

A small DC motor, mounted on a heavy base plate, is connected by means of an eccentric bearing and connecting rod to a small walking beam. This beam is composed of two $1\frac{1}{4}$ inch Dural angle strips

* Read at the Fall Meeting, Houston, Nov. 19, 1937. Published by permission of the Board of Directors, Humble Oil and Refining Company.

† Humble Oil and Refining Company, Houston, Texas.

13 inches long fastened securely to the upright of the steel base plate by means of two flat springs 0.017 of an inch thick. The eccentricity of the bearing on the connecting rod and motor shaft is adjustable from 0.02 to 0.002 of an inch. Rheostats in both the field and armature circuits of the 6-volt motor serve for regulating the frequency of displacement of the beam.

Fig. 1 shows a schematic diagram of the apparatus used in these measurements. The seismopickup is of the variable reluctance type. It is clamped rigidly between the Dural angle strips about one inch

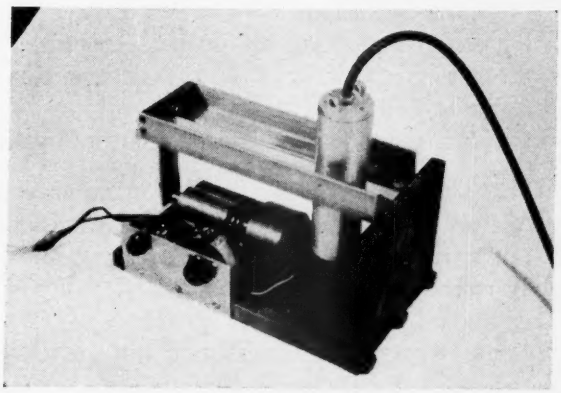


FIG. 1 (a)

from the hinged end of the beam. With the eccentric bearing adjusted to give a displacement of the seismopickup of 0.003 of an inch, constant amplitude of displacement with frequency is obtained up to approximately 20 cycles per second. By means of a mirror system fastened to the base plate, and connected to the beam at the seismopickup position by a silk thread, the amplitude of motion is obtained for the higher frequencies. The motion of the beam is sinusoidal up to approximately 60 cycles.

The reflection shot is recorded with the seismopickup in its regular position and at a sensitivity level comparable with the other channels of the system. At this same sensitivity level, the seismopickup is placed in position on the shaking beam, the deflection of the galvanometer is adjusted to that of the recorded reflections, by means of the T-pad attenuator, and the frequency of the shaking beam is adjusted to that of the reflections as indicated on the seismogram. The attenua-

tion factor, K, is determined from the decibel reading of the attenuator pad and the ratio of E_1/E_2 is obtained.

We shall show later that at a given frequency and over the amplitude range involved, the output voltage of the seismopickup was found to be proportional to the amplitude of motion, or that

$$A/E_1 = a/E_2$$

and

$$a = A/K,$$

where A = the corrected amplitude of motion of the seismopickup on the shaking beam,
E_1 = the unattenuated voltage of the seismopickup on beam,
E_2 = the attenuated voltage of the seismopickup = Voltage due to Reflection,
a = the amplitude of ground motion produced by the reflection.

In Fig. II are shown the values obtained for this ground motion in different areas, together with the dynamite charges necessary to produce these values for reflections arriving between 2.5 and 3.0 seconds; approximately 10,000 feet.

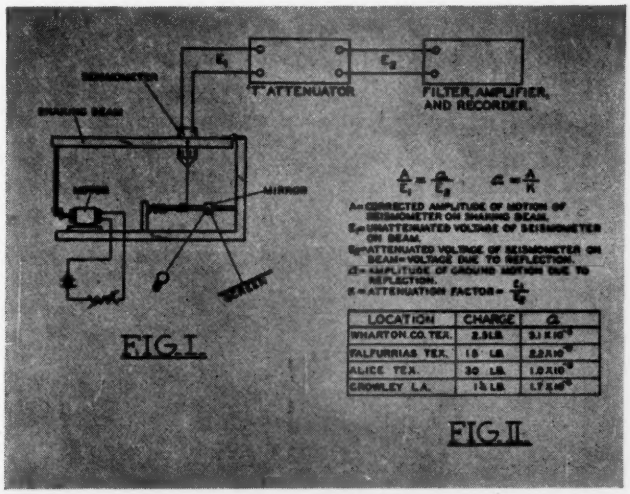
COMPARISONS BETWEEN ELECTRICAL AND MECHANICAL SEISMOGRAPH

In order to determine whether the voltage output of the seismopickup is linear with amplitude of displacements, comparisons were made between the electric seismometer and a mechanical seismograph, Displacements of the order of 10^{-4} to 10^{-5} inches were measured with a mechanical seismograph at a frequency of 45 cycles and the seismometer system referred to these levels. A linear relation between these two instruments was obtained at this frequency over this amplitude range. The mechanical seismograph had a period of 2.2 seconds, a dynamic magnification of 3600 at this frequency (45$\sim$), and was critically damped.

The unrest on the concrete pier in the basement of the Humble Building, where these comparisons were made, is usually of the order of 10^{-5} inches at frequencies of from 3 to 15 cycles, and 10^{-6} inches from 20–60 cycles.

Additional checks on the linearity of the seismopickup were made using a large tuning fork located near the Pierce Junction oil field. A picture of the fork is shown in Fig. 3.

Magnification of the amplitude of vibration at a given position on the fork tyne was obtained by means of an optical lever similar to the one used on the shaking beam. A magnification of 4500 was obtained.



LOCATION	CHARGE	G
WHARTON CO. TEX.	2.5 LB.	2.1×10^{-5}
VALFURRIAS TEX.	15 LB.	2.2×10^{-5}
ALICE TEX.	30 LB.	1.0×10^{-5}
CROWLEY LA.	15 LB.	1.7×10^{-5}

FIG. I, FIG. II.

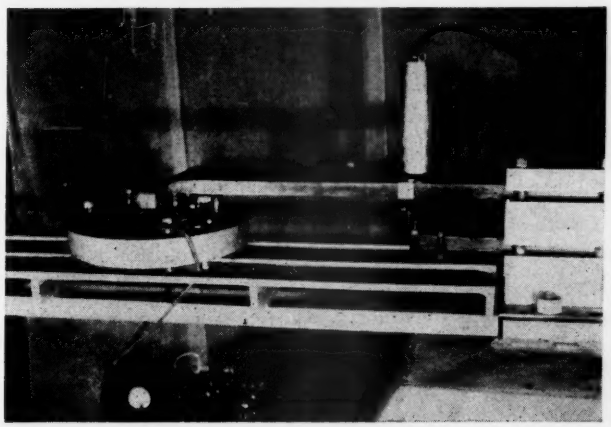


FIG. 3

The fork was driven at two amplitudes of vibration in the ratio of 10:1. The frequency of vibration was 48 cycles per second. The seismopickup was first placed at a point on the fork where the amplitude was measured by the optical lever, and the fork amplitude was

varied to the two values mentioned above. The seismopickup was connected through an amplifier to a recording galvanometer. The amplitude of the two oscillograms obtained bore the same relation as the fork amplitudes, showing that the seismopickup was linear within the two amplitudes of the fork. The fork was again adjusted to the larger amplitude and the seismopickup moved to a point where the galvanometer trace corresponded to the smaller amplitude of the fork at the previous position. Thus the amplitude of vibration at this second point was 0.1 that of the former. The deflection of the galvanometer was then increased by a factor of 10 by adjusting the gain control of

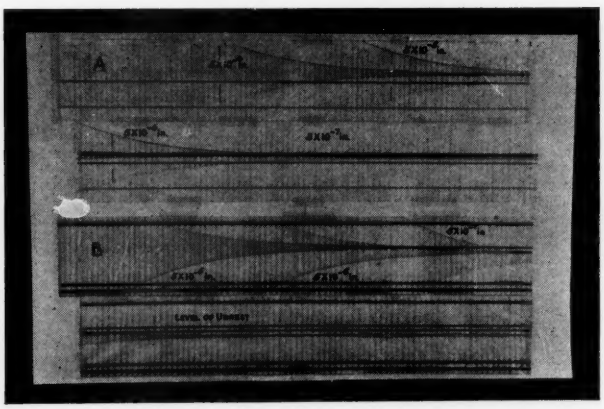


FIG. 4

the amplifier, and when the fork was driven at the smaller amplitude, the deflection of the galvanometer decreased to 0.1 of the previous deflection. This procedure was repeated and points on the fork and on the concrete base of the fork were found where the amplitude of vibration ranged from 10^{-3} to 10^{-7} inches. Like results obtained over this range of amplitudes. Thus, if the transmission medium, the fork base, is linear, the seismometer is linear. It is difficult to believe that the transmission medium is non-linear; for, according to the results of these experiments, the non-linearity of the transmission medium would have to be counteracted by a similar non-linearity of the seismopickup of opposite sign. Therefore, at a given frequency the output voltage of the seismopickup is considered to be proportional to the amplitude of vibration over this range of amplitudes.

Fig. 4 shows two records taken of the decay of the tuning fork. A

seismopickup placed on the fork at a position of known amplitude, was connected to 3 similar recording channels having gain ratios of approximately 10:1. The fork was driven at a known amplitude and then allowed to decay. Record (A) in Fig. 4 shows the decay from 5×10^{-4} to below 10^{-7} inches. Record (B) shows this decay down to 10^{-8} where the vibrations were interfered with by the unrest caused by the operations in the nearby oilfield.

Comparisons made between the amplitude of the fork and the shaking beam indicate that the measurements made in the field with the shaking beam are reliable.

I acknowledge with pleasure the cooperation and assistance given in this work by Dr. B. O. Winkler, Mr. C. C. Nash and Mr. C. C. Palmer of the Humble Geophysics Research Division.

A MILITARY ASPECT OF EXPLORATION GEOPHYSICS*

E. ROANE MELTON†

ABSTRACT

That branch of exploration geophysics using refraction and reflection methods of seismographing, employs equipment and methods similar to military sound ranging. Present methods and equipment used in geophysical seismographing show results from developments in the art of sound ranging during the last war.

The accuracy obtained in sound ranging is considerably greater than that obtained in refraction shooting where the air wave is used to measure distance. Corrections are applied for direction and velocity of wind, and for temperature.

Personnel in the sound ranging unit is organized similar to a geophysical field crew, having motor truck transportation, instrument operators, and record interpreters. However, the geophysical crew is more of a mobile outfit.

In any future war, the geophysical personnel, particularly the exploration geophysicist, will be expected to place his specialized training at the disposal of the government.

Turn through ninety degrees either exploration geophysics or military sound ranging and you have the other science or technique, whichever it may be called. Refraction and reflection methods of seismographing employ sound waves in a vertical plane; sound ranging employs sound waves in a horizontal plane.

Sound ranging, as that term is applied in military science, embraces the procedure of locating the source of a sound such as a gun report or a shell burst, by calculations based upon the propagated sound wave. The actual set-up consists of six microphones placed at known points on an arc of a circle, or on a straight line, depending on the conditions of the terrain, each microphone being connected to one element of a recorder. A curved line is preferred for the microphones because of greater ease in record interpretation. When a sound wave is propagated through air by a gun report or a shell burst, the wave reaches each of the six microphones at a time dependent upon the position of the sound source. The differences in time of arrival of the sound wave at the various microphones, when plotted on a suitable terrain board having functions of time and position, locates the source or point of origin of the sound. It can readily be seen that the two fields of sound measurement have much in common. The procedure of sound ranging will be discussed later only in a comparative sense, as obviously a detailed discussion of the equipment and technique is not permissible.

* Paper read at the Fall Meeting, Houston, Texas, Nov. 19, 1937.

† Seismic Explorations, Inc., Houston, Texas.

Prior to the last European war there was no service in the United States Army analogous to those which grew up under the conditions of position warfare since the latter part of 1914, for the purpose of locating the position of active enemy artillery and for directing the fire of friendly artillery on these positions. In the Spring of 1917, a visiting committee of French officers persuaded the United States military authorities to experiment with sound ranging equipment. In July and August of 1917, intensive construction work on experimental equipment went forward at the National Bureau of Standards and at Princeton University. The work at the Bureau of Standards was under the active supervision of Burton McCollum, while H. B. Williams was in charge of the work at Princeton. It is interesting to know that at the present date there are five men, McCollum, Fecht, Karcher, Eckhardt, and the speaker, actively engaged in exploration geophysics who were in the Bureau of Standards group developing sound ranging equipment.

The equipment developed and built at the Bureau, called the T-M apparatus (Télégraphie Militaire), used a continuous strip of smoked paper as the record. One compartment of the recorder contained a roll of paper which as it was unwound became smoked on one side by a kerosene lamp. The smoked paper passed over a rotating drum, at which point six coil type galvanometer elements with pointers resting on the smoked surface, and connected to the six microphones, gave traces of microphone activity. For timing, a tuning fork controlled synchronous motor, with commutator type segments, operated a seventh pen to put time marks on the record. The record was then paraffined to give a permanent trace which could be handled for interpretation. A carbon button type of microphone was used with this equipment.

At Princeton University the Einthoven string galvanometer was employed. In England, prior to the war, a galvanometer with a single gold-plated quartz string had been in extensive use for physiological work. When England's military service demanded six strings, an instrument was built which, though large, cumbersome, and relatively inefficient, accomplished its application in a satisfactory manner. Fig. 1 shows the galvanometer with the camera. Tungsten and platinum wires 14μ in diameter were used for fibers. An optical magnification of 30$\times$ was obtained at 40 inches. This same galvanometer, Fig. 2, with slight modifications, was used in the United States equipment. Where the British used a large automatic camera in which

the moving photographic paper was sprayed with developer, the Princeton equipment used a small automatic developing camera in

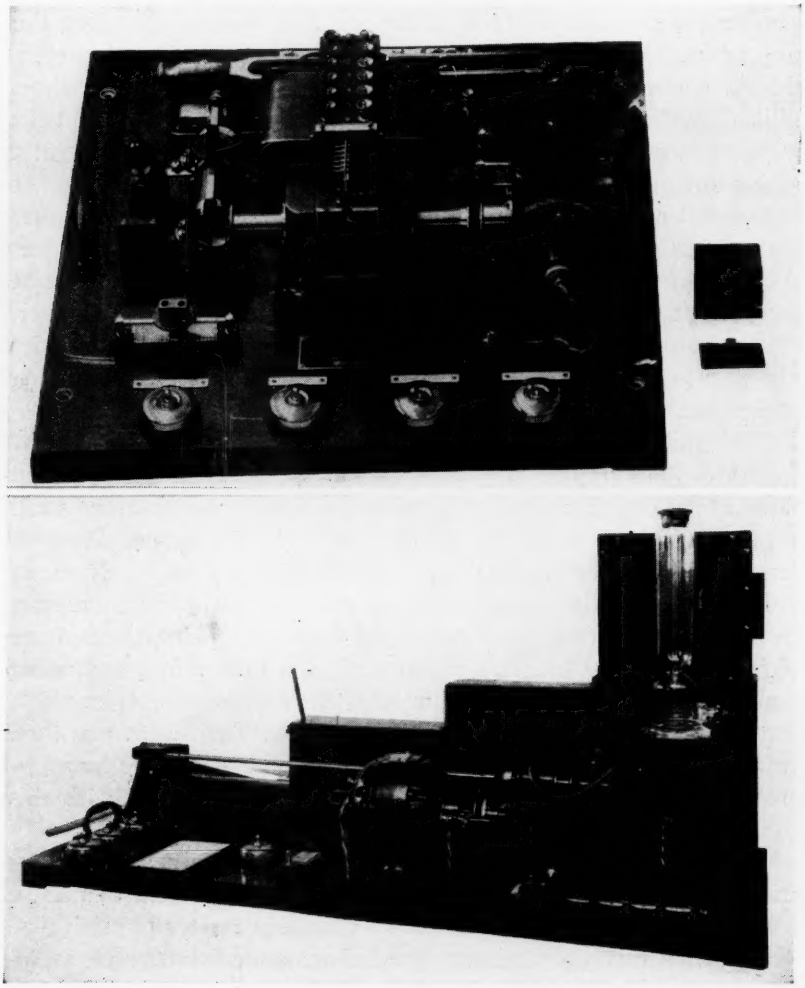


FIG. 1

which the 3.5 cm. record strip dipped into developing and fixing solutions. With this outfit the hot wire type of microphone was used.

These two groups made a definite contribution to the art of exploration geophysics. The Bureau of Standards group without a

doubt were the first in this country to see the significant possibilities of employing sound waves in the manner that developed into reflection

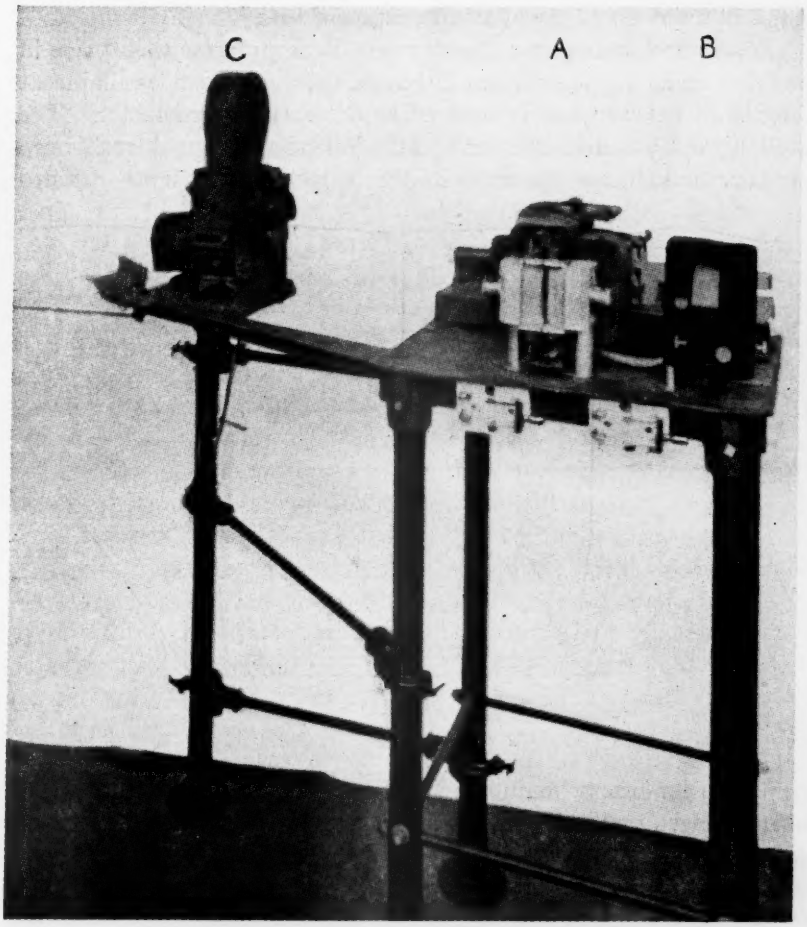


FIG. 2. Galvanometer and camera. A, galvanometer; B, lamp and time wheel; C, automatic developing camera.

exploration, although their work was not made public until several years after their initial investigations.

From the work at Princeton emerged the multi-string galvanometer so well known in present geophysics. From the heavy, massive multi-string galvanometer for sound ranging Williams designed a

small single string instrument of much greater efficiency, and which later became available with multi-strings. In addition, he designed a continuous non-developing camera, modifications of which can be found in many geophysical seismographs of today.

For several years after the war very little progress took place in sound ranging developments, although the equipment available at the end of the war was recognized as not entirely satisfactory. The civilian work was discontinued and the military personnel transferred to other branches of the service, due to lack of sufficiently trained

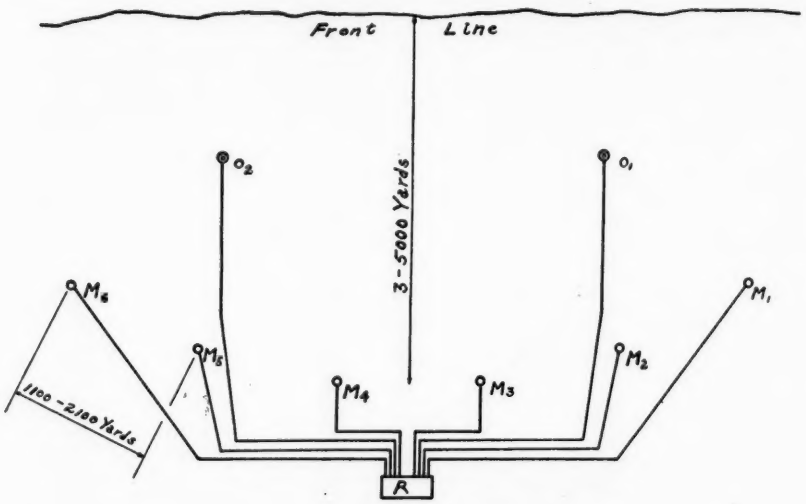


FIG. 3

personnel for proper maintenance of such units. However, this has now changed, military personnel being actively trained in sound ranging, and active development of equipment taking place. As now instituted in the reorganization of the Army, the sound ranging unit is the Observation Battalion, Field Artillery. Present equipment uses both the string galvanometer and the mirror type oscillograph, with automatic developing camera running at the rate of 6 inches per second, with 0.01 second time intervals. Three types of microphones are being tested for adaptability.

Fig. 3 shows a typical sound ranging installation, M_1 to M_6 being microphones equally spaced 1100 to 2100 yards on an arc of a circle. O_1 and O_2 are outpost observers who will hear the sound wave several seconds before it reaches any of the microphones. The instant either

observer hears a pertinent sound wave, he presses a key which starts the recorder operating. After the recorder has run sufficiently to record the series of waves, it is stopped by personnel at the recording station, and does not again operate until an outpost starts it.

Visualize an outpost observer in a hazardous location charged with the duty of discriminating between certain sounds, and one can wonder how the question of personal error or human element will control the selective ability under such conditions. Undoubtedly there would be a distinct advantage in having a mechanical outpost with no element of fatigue or possible varying degree of selection. In the geophysical field, operations are based on directional response within frequency limits and timed intervals. Therefore it is conceivable to think of an outpost consisting of an electronic relay with frequency selective qualities, having a wide angle of directional response or an acute angle of response. Inasmuch as the sound ranging unit is organized to function continuously for 24 hours a day, the outpost problem is a major question.

The act of firing a gun creates three principle types of sound waves: the gun wave, sometimes called the muzzle wave, the burst or detonation wave, and the shell wave. When a gun is fired, the powder gases emerging from the muzzle create a pressure wave; this is the gun wave and is of low frequency and high intensity, as shown in Fig. 4. Within the application of sound ranging, the fundamental of the gun wave is usually below audibility and it is the harmonic which is heard by the ear. The gun wave is used when locating hostile guns or batteries.

The burst or detonation wave is the wave set up by the bursting of the projectile. This wave is recorded when it is desired to adjust friendly artillery by means of sound ranging. This wave has no recognizable fundamental, since it is extremely irregular in shape; but by knowing the approximate direction and time of flight of the projectile, its characteristic can readily be selected on the record.

The shell wave is sometimes called the ballistic or bow wave. In front of all field and high velocity guns a double report is heard when the gun is fired. The first report is due to a sound wave produced by the motion of the shell through the air with a velocity greater than that of sound; the second report is due to the explosive in the gun. The shell wave spreads out in the form of the surface of a cone, of which the shell is the apex. When this surface passes over the listener, the report is heard. This cone ceases to be generated at the instant the

feet can be obtained under average conditions, after correcting for temperature, wind velocity and character. At the end of the war, military sound ranging was giving an accuracy of 75 feet in 16,000 feet, or an accuracy of 0.45%. With present equipment an accuracy slightly better than 0.5% is being obtained for ranges up to 30,000 feet. The accuracy will be slightly better than this for deflection.

Time scales on the plotting board and spacing of microphones in sound-seconds are based upon a velocity of sound of 369.2 yards (337.6 meters) per second, (velocity of sound in still air at 50°F. (10°C.)) at an assumed constant mean humidity. Variations in humidity from the assumed mean have but slight effect and are disregarded. The velocity of sound, in air saturated with moisture, at 50°F. (10°C.), is one yard, or less, per second greater than in dry air. However, corrections are applied for velocity and direction of wind, and for temperature. In the present set-up, atmospheric correction is the limiting factor of accuracy as the final plotting can be done with great precision.

Each sound ranging unit has attached to it a meteorological section for determining the pertinent atmospheric conditions. For direction and velocity of wind, a small balloon is released and its ascension followed so as to measure the horizontal and vertical angles at one minute intervals for four minutes, or normally to a height of three thousand feet. Percentages of the indicated velocities and azimuths are used as correction factors for velocity and direction of wind.

Temperature correction is obtained by instruments in a captive observation balloon at a 500 foot level, if the balloon is available. If it is not available, ground temperature is measured and from previously plotted curves the temperature at the 500 foot level is deduced.

The disadvantage of obtaining weather corrections by the above methods immediately becomes apparent. If the wind balloon is visible to the meteorological section, it also can be visible to the enemy, and immediately informs the enemy that some unit is in operation in that locality. Though the sound ranging unit is screened from enemy air observation, the enemy artillery can still place sufficient shells in the area to make it decidedly uncomfortable, and possibly disrupt operation of the equipment. Thought is being given to the possibility of determining wind corrections by measuring the drift of smoke puff from an explosive shell in the air fired by friendly artillery. Even this would not completely solve the problem, as use of the smoke puff is

velocity of the projectile falls below that of sound. When this occurs, the shell wave loses its conical shape and grows round at the wave front. Accordingly, it is evident that the difficulty of utilizing the shell wave becomes very great, as the source is moving instead of fixed and the wave itself changes shape.

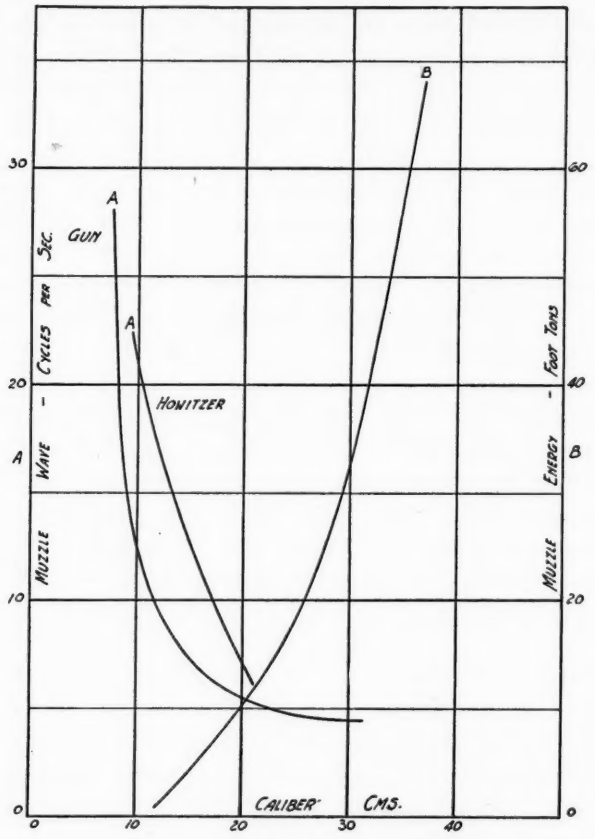


FIG. 4

Since the sound wave is propagated through air, its velocity is affected by atmospheric conditions. Before discussing any figures relating to accuracy of military sound ranging, it is desirable to emphasize that any definite figures given are based on data obtained from sources considered to be thoroughly reliable and unprejudiced. From information available, it is understood an accuracy in the order of 2% for air shots in refraction shooting over distances less then 15,000

limited to visibility, the same as the ascension balloon, Also. this still leaves unanswered the question of the balloon for temperature.

As previously mentioned, the differences in time of arrival of the sound wave at the microphones are determined, giving five time differences for six microphones. Theoretically the most simple method of plotting these time differences is by means of a circle whose circumference is tangent to the five circles having as radii, the time difference at each microphone multiplied by the sound velocity, the center of the touching circle being the source of sound, or gun. As there is no simple geometrical method of finding the center of the touching circle within the scale of plotting, hyperbolic plotting is used, and actually the asymptote of the hyperbola is used. Consequently, a correction must be made for this substitution.

To the geophysicist there will immediately come the thought of utilizing the seismic wave created by the gun mount, but along with that thought will come the picture of geological discontinuities with which he is so familiar. The seismic wave would be ideal, as only the asymptote correction would be necessary. In addition to the problem of geological formation, there is the consideration of the amount of energy imparted to the ground by the gun mount. Modern gun recoil systems are relatively efficient absorbers. Mintrop reported that sound ranging by means of the seismic wave is impossible because of the low energy. It should be pointed out, though, that Mintrop used a mechanical seismograph whose sensitivity was far below modern electrical methods. To offset the small amount of energy imparted to the ground by the gun, consider the electronic amplification now being used in exploration geophysics—one would hardly say the ultimate has been reached.

The weather corrections and asymptote correction are determined from previously prepared tables and charts. The corrected time intervals are plotted on a coordinate board representing the area under observation. Coordinates of the point of intersection of the time rays are telephoned to friendly artillery. By knowing the time and approximate direction of flight of a friendly shell, it can be ranged for point of impact or burst, and suitable corrections given to the firing gun. With a well-trained personnel a set of coordinates can be given to the firing gun in 3 minutes after the record comes out of the camera.

The Observation Battalion is organized in a manner very similar to that of a geophysical field crew, all equipment being installed in or handled by motor trucks. If geodetic points and data are available

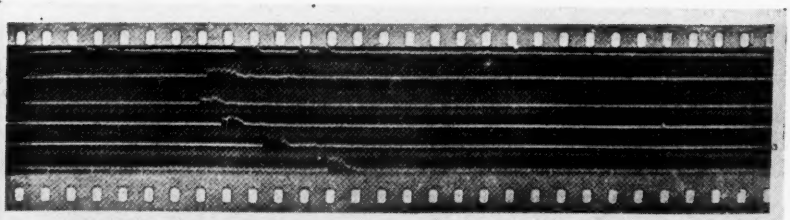
for tying-in microphone positions, the unit can be ready for operation 5 hours after arriving at a location.

The operator of the recorder has much the same function as a geophysical observer. He is responsible for the correct functioning of the equipment with its pertaining electrical apparatus. The record interpreter corresponds to the geophysical office man—he selects the time breaks on the record and applies the corrections. It is usually possible to determine the particular gun firing and its caliber, for from Fig. 4 can be seen the relation of the gun caliber and the emitted gun wave. In addition to its wave frequency, each gun will have a characteristic wave shape which soon becomes apparent to an experienced record interpreter. Fig. 5 shows some typical records.

Lately there has been much publicity on the mechanization of various armies and that any future war will be one of fast changing situations as a result of the increased mobility. The purpose here is not to discuss the pros and cons of this possibility but an assumption of great mobility can be considered, with its effect on present methods of sound ranging. At the present time, tactical employment of sound ranging is considered feasible on guns of 105 mm. caliber and above, in a stagnant or consolidated warfare, although under certain conditions ranging can be done on the 75 mm. gun. It is difficult to estimate at what caliber fast mobility will be limited in the future as developments are rapidly taking place in capacity of carriers and tractor type of equipment. If the situation is one of speed, then the present sound ranging service is not designed for future operation. Greater portability of equipment and speed of installation must be emphasized, as the geophysical crew does today. Instead of employing three or four trucks for a recording station, they must be consolidated into one.

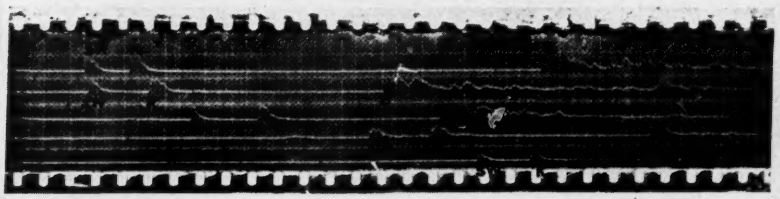
Possibly greater speed should be developed so the 75 mm. guns can be ranged, and also the 75 mm, projectiles, in a changing situation. Without a doubt advancing infantry will at times be thankful for counterbattery fire on emplaced 75 mm. guns. Certainly sound ranging need not be considered for smaller calibers, such as the 37 mm. because of its tactical use. Highly mobile, being really portable, the 37 mm. gun is effective only on a direct hit which limits its use to visibility and short range, its effective range being 5000 feet.

In the latter part of 1935, the War Department, after representations were made to it, recognized the possible relationship between military sound ranging and exploration geophysics. Consequently during the early part of 1936, a committee representing the War



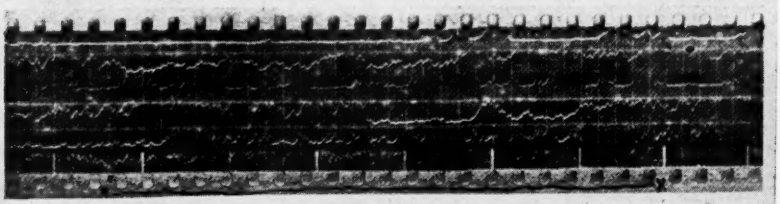
A. Record of a German Howitzer

This shows how the pressure wave created when the gun was fired makes a "break" at the instant at which it reaches the corresponding microphone. Vertical divisions correspond to 1/10 sec., and these are sub-divided to read to 1/100 sec. It also shows how the regular spacing of the microphones cause the breaks to form a regular pattern



B. Record of a 77 mm. Field Gun

This shows the (SW) shell wave, (R) report, and (B) burst. Much information can be gathered from a film such as this by inspection only. We can see that the gun must be nearly opposite the two microphones on one flank as the report arrives at these almost simultaneously. It is a long way back because the breaks made by the report form a convex pattern. The bursting shell must be opposite microphones 2 and 3, and nearest 3, and somewhere near the base as these breaks form a very deep curve. We know that it is a gun and not a howitzer that is firing from the presence of breaks caused by the shell-wave. Something might be learned of the calibre of the gun from the characteristics of the gun report break. Compare these with those shown on record A



C. Record of a High Velocity Gun

This is the record of a gun firing made in the Ypres Salient on July 24, 1917, just prior to the Third Battle of Ypres. From this record the computer was able to locate a gun, and it is reproduced here to enable the reader to see why skill and experience were needed to read these films when the front was active

FIG. 5

Department was sent to Texas to investigate the art of geophysical seismographing. This committee after examining field and office operations made a report pertinent to the exploration geophysicist, in that, (1) the equipment used in geophysical seismographing can with little modification be used for sound ranging, and (2), the geophysical personnel has an excellent training suitable for sound ranging officers, and in an emergency should be utilized for this purpose.

There is now being organized in Houston, a reserve sound ranging unit whose officers are to be drawn from the geophysical profession. It is hoped that through the experience and future training of these officers, answers will be found for the several previous questions.

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ON THE FIELD DUE TO A VERTICAL LINE SOURCE OF CURRENT GROUNDED TO EARTH*

SOLOMON BILINSKY†

ABSTRACT

An expression for the current density at any point in the earth due to a current in an infinitely long vertical wire is found for two types of current: (1) Simply periodic, (2) Rectangular impulse. These are given respectively by equations (11) and (13) below, where I_r is the horizontal radial component and I_z the vertical component of the current density vector at the point (r, z), which is at a distance R from the grounding point. These formulas hold for frequencies not too high or times not too small to allow neglect of the displacement current.

1. If one imagines an infinitely long wire brought perpendicularly to earth, and also grounded at the infinitely distant terminus, there arises the problem of finding the distribution of currents in the earth excited by a given current in the wire. For a constant current in the wire the solution is elementary and is well known. We shall be concerned here with finding a solution for two other types of current flow: (1) an oscillating steady state having a sinusoidal frequency $\omega/2\pi$, and (2) an instantaneous change from one constant value to another, which is a transient state.

Although this problem is largely an artificial one, its claim upon our interest resides in the fact that the solution is obtained without much difficulty, and is, moreover, expressible in terms of a simple combination of well-known functions. This fact alone is enough to excite a theoretical physicist with awe, no matter how useless the problem. It is hoped, however, that the solution of the problem may serve more than the interests of esthetics or curiosity.

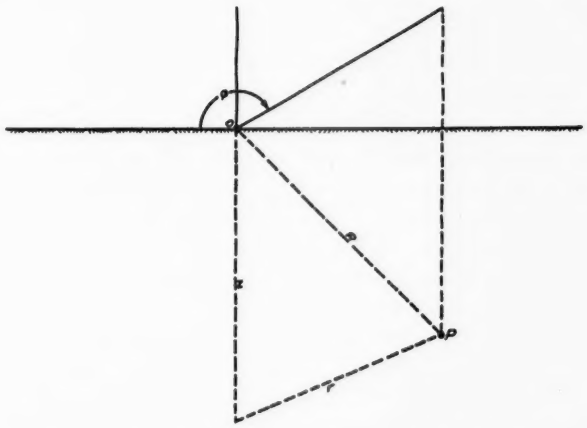
For the purpose of complete amenability it is assumed that the earth is a semi-infinite homogeneous and isotropic conductor, separated by a plane boundary from an equally regular dielectric (air). There is also supposed to be neither hysteresis nor chemical dissociation. With these conditions the Maxwell equations are applicable.

2. The cyclindrical symmetry of the problem indicates that cylindrical coordinates are the most appropriate. It is physically obvious from the condition of symmetry that the azimuthal component of the electric field E_ϕ, as well as both the vertical and radical components

* Read at the Fall Meeting, Houston, Nov. 19, 1937.

† Subterrex, Houston, Texas.

of the magnetic field, H_z and H_r, respectively, are all zero. The fact that the only surviving component of H is H_ϕ greatly simplifies the problem.



We take the half-space $z<0$ to be filled with the dielectric (air) for which the dielectric constant ϵ, and permeability μ equal 1, and the conductivity $\sigma=0$. The conductor (the earth), where $z>0$, has $\mu=1$. The source is at the origin O, and an arbitrary point within the medium at P. Our first problem is to find the current vector at P as a function of the time when the current at O is $I_0e^{-i\omega t}$.

3. In cylindrical coordinates the Maxwell equations, subject to the conditions of symmetry, become, for the field within the conductor, the following:

$$(1) \qquad \frac{1}{c}\dot{H}_\phi = \frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r}$$

$$(2) \qquad \frac{1}{c}(\epsilon\dot{E}_r + 4\pi\sigma E_r) = \frac{\partial H_\phi}{\partial z}$$

$$(3) \qquad \frac{1}{c}(\epsilon\dot{E}_z + 4\pi\sigma E_z) = \frac{1}{r}\frac{\partial}{\partial r}(rH_\phi).$$

These quantities are in conventional units, that is, the magnetic field is measured in E. M. U. and everything else in E. S. U.

We shall speak of ordinary frequencies as those that satisfy the inequality $\omega \ll \sigma$. (For an earth resistivity of 9000 ohm-cm. $\sigma=10^8$.) Consequently for ordinary frequencies the displacement term $\dot{E}\epsilon$ is

negligible compared to the current term $4\pi\sigma E$, and in place of the equation (2) and (3) we have the following:

$$\frac{4\pi}{c} I_r = -\frac{\partial H_\phi}{\partial z} \tag{4}$$

$$\frac{4\pi}{c} I_z = \frac{1}{r}\frac{\partial}{\partial r}(rH_\phi) \tag{5}$$

where I the current density vector equals σE. These equations clearly indicate that a solution is to be simply obtained by solving first for H_ϕ, and evaluating I by differentiation.

4. The differential equation for H_ϕ, obtained from the Maxwell equations is the following:

$$\frac{4\pi\sigma}{c^2} H_\phi = \frac{\partial^2 H_\phi}{\partial r^2} + \frac{1}{r}\frac{\partial H_\phi}{\partial r} - \frac{H_\phi}{r^2} + \frac{\partial^2 H_\phi}{\partial z^2}. \tag{6}$$

Since we have assumed a simply periodic source, we write $H_\phi = H_\phi e^{-i\omega t}$, where H_ϕ is a function of the coordinates alone. An elementary solution of (6) is given by the equation

$$H_\phi = e^{-z\sqrt{\alpha^2 - k^2}} J_1(\alpha r)$$

where α is an arbitrary constant, but k satisfies the equation

$$k^2 = \frac{4\pi i\sigma\omega}{c^2}. \tag{7}$$

For $\omega = 0$, our solution for H_ϕ must reduce to the solution for the steady direct current state. But in that case H_ϕ must satisfy the equation

$$H_\phi = \frac{2I_0}{cr}\left\{1 - \frac{z}{R}\right\} \tag{8}$$

as one might see by integrating equation (5), noting that $I_z = \dfrac{I_0 z}{2\pi R^{3/2}}$ in that case. Now (8) may be written as a definite integral, as follows:

$$H_\phi = \frac{2I_0}{c}\int_0^\infty e^{-\alpha z} J_1(\alpha r)\, d\alpha.$$

This broadly suggests that we ought to study the integral:

$$\frac{2I_0}{c}\int_0^\infty e^{-z\sqrt{\alpha^2-k^2}}\,J_1(\alpha r)d\alpha. \tag{9}$$

We may write this integral in the following form:

$$H_\phi = -\frac{2I_0}{cr}\int_0^\infty e^{-z\sqrt{\alpha^2-k^2}}\frac{d}{d\alpha}J_0(\alpha r)d\alpha,$$

and integrate by parts. We get the equation

$$H_\phi = \frac{2I_0}{c}\frac{e^{ikz}}{r} - \frac{2I_0}{c}\frac{z}{r}\int_0^\infty \frac{e^{-z\sqrt{\alpha^2-k^2}}}{\sqrt{\alpha^2-k^2}}J_0(\alpha r)\alpha d\alpha.$$

The integral here is that given by Sommerfeld in his well known treatment of wireless telegraphy.[1] The result is that for H_ϕ we have the equation

$$H_\phi = \frac{2I_0}{cr}\left\{e^{ikz} - \frac{z}{R}e^{ikR}\right\}. \tag{10}$$

5. On the boundary $z=0$, we have, from (10), that $H_\phi = 2I_0/cr$, which confirms the boundary condition that exists for an infinite wire that is normal to the boundary plane. The boundary condition on E_r, requiring that it be continuous is approximately satisfied, and exactly so if $\omega/\sigma=0$ in the limiting case.

The corresponding expressions for I_r and I_z, suppressing the time factor, are the following:

$$\begin{aligned} I_r &= \frac{I_0}{2\pi r}\left\{\frac{r^2}{R^3}e^{ikR} + \frac{ikz^2}{R^2}e^{ikR} - ike^{ikz}\right\} \\ I_z &= \frac{I_0 z}{2\pi}\left(\frac{1}{R^3} - \frac{ik}{R^2}\right)e^{ikR}. \end{aligned} \tag{11}$$

6. Let us now suppose that the source changes instantaneously from a strength I_0 to a strength 0 (no current). In place of a time factor $e^{-i\omega t}$ we choose $e^{-w^2 t}$ in order to construct a solution with the desirable properties. These will be verified later.

In place of (10) we now have the same formal equation

[1] See Frank u. von Mises, "Differentialgleichungen der Physik," p. 924, Vol. II, 1935.

$$H_\phi = \frac{2I_0}{cr}\left\{e^{ikz} - \frac{z}{R}\,e^{zkR}\right\}e^{-w^2t}$$

having written in the time factor, but k now has the value $w\sqrt{4\pi\sigma}/c$. We can see that this solution is made up of terms of the form e^{-w^2t} $e^{iw\xi}$, where w and α are constants, and ξ is a variable distance. Among the standard solutions formed from this expression there is the following one:

$$\frac{2}{\sqrt{\pi}}\int_0^{\xi/2\sqrt{\alpha/t}} e^{-\lambda^2}d\lambda.$$

Let us denote this last expression, which is the error function, so-called, by $\psi(\xi/2\sqrt{\alpha/t})$. We may then easily construct the following solution for H_ϕ

$$H_\phi = \frac{2I_0}{cr}\left\{\psi\left(\frac{z}{c}\sqrt{\frac{\pi\sigma}{t}}\right) - \frac{z}{R}\,\psi\left(\frac{R}{c}\sqrt{\frac{\pi\sigma}{t}}\right)\right\}. \tag{12}$$

This is the solution whose properties we are to examine. We find that it satisfies the following boundary conditions:

When

$$t = 0 \qquad H_\phi = \frac{2I_0}{cr}\left\{1 - \frac{z}{R}\right\}$$

$$t = \infty \qquad H_\phi = 0$$

$$z = 0 \qquad H_\phi = 0$$

$$z = \infty \qquad H_\phi = 0.$$

Hence, this is the solution sought.

7. The expression for I_z and I_r are easily found by differentiation, according to (4) and (5). We first write h for $\frac{1}{c}\sqrt{\frac{\pi\sigma}{t}}$, $\psi'(x)$ for $\frac{d}{dx}\psi(x)$. Then we have

$$I_r = \frac{I_0}{2\pi}\left\{\frac{r}{R^3}\psi(hR) + \frac{z^2h}{rR^2}\psi(hR) - \frac{h}{r}\psi'(hz)\right\},$$

$$I_z = \frac{I_0 z}{2\pi R^2}\left\{h\psi'(hR) - \frac{\psi(hR)}{R}\right\}. \tag{13}$$

REVIEW

Introduction to Theoretical Seismology, Part I, Geodynamics. J. B. Macelwane, S. J., John Wiley & Sons, New York, 1936. x+366 pp., $6.00.

The volume is a companion to another characterized as Part II and entitled Seismometry by F. W. Sohon, S. J. The present volume is a source of a great deal of valuable information, especially for one interested in beginning a study of earthquake lore and eager to form a foundation in that field. Of particular value in this connection is the completeness of the bibliography.

It is proposed to review this volume from the point of view of the seismologist primarily interested in exploration work. Those of us engaged in applied seismology would do well to pay more attention to the work that is being and has been done in the domain of earthquake seismology. Immediate benefits will be derived from an examination of the methods of computations and interpretations employed in studying the paths of earthquake waves. A knowledge of the theories of the various types of waves, *per se*, and of the development of these theories from those of stresses and strains in elastic media, will be of immense value.

The volume consists of an introduction and eleven chapters. The first three chapters are entitled: I. Stresses in an Elastic Solid, II. Elastic Strain, III. Relations between Stress and Strain. The Chapters cover the mathematical treatment of these subjects but it is not quite clear to the reviewer just how much knowledge of mathematics the author expects the reader to have. On the one hand, it is evident that certainly a reasonable facility with the tools fashioned in a good course in advanced calculus is required and on the other hand there are pages and pages of simple algebraic manipulations which could easily have been omitted except for the final forms of the desired expressions. The reader, for whom all these algebraic steps are necessary, can hardly be expected to gain anything from the Divergence Theorem and related topics—and the reader who can follow these things will have short patience with what he must consider puerile.

On the whole, however, the author "gets there" with his material. The professional mathematician will take a great deal of exception to the lack of any semblence of rigor, and, to the novice, these mathematical chapters and those that follow will be, it is feared, none too clear.

Chapters IV and V are each subdivided into two parts:

IV. Elastic Body Waves.
  Part 1: Waves in the Interior of an Isoptropic Elastic Solid.
  Part 2: Waves in a Gravitating, Compressible Planet.
V. Surface Waves on the Plane Boundary of an Isotropic Elastic Solid.
  Part 1: Rayleigh Waves.
  Part 2: Love Waves.

These two chapters, also, are mathematical in content and their aim is to follow through the equations of motion previously developed and draw the conclusions concerning various types of waves. Here the treatment is one of mathematical manipulations only, the necessary integrations being performed from the point of view of "ingenious devices" rather than that of physical intuition.

The next chapter, VI. Vector Treatment of Elastic Waves, was written by S. W. Sohon, S. J. It is an excellent example of what can be done with the proper mathematical

tools in clearness and brevity, once these proper tools—vector analysis, in this case—have been mastered.

Of greatest immediate interest to the exploration geophysicist will be the next two chapters: VII. Reflection and Refraction of Elastic Waves, and VIII. The Paths of Seismic Rays. Unfortunately, the reviewer can nowhere find a clear statement of the "path of minimum-time" principle and the consequent formulation of the elementary Snell's Law. The importance of an emphasis on this matter is such that the treatment on page 150 can hardly be considered ample. However, if read carefully, the results in these chapters will be highly profitable to one interested in interpretation theory of applied seismology. The second of these two chapters, in particular, can serve the well-grounded computer in reflection seismograph work, even though here, too, he must disregard the lack of mathematical rigor and assume the results valid, as indeed they are.

The remaining chapters: IX. Interpretation of Seismograms, X. Determination of Epicenters, and XI. Depth of Focus, are very fascinating and clearly presented. They offer the actual work done with earthquake seismograms, locating the sources of the disturbances, explaining the conclusions derived concerning the earth's crust. These chapters abound in citations to pertinent literature and contain numerous valuable tables of the seismological science.

Two short appendices, a list of symbols, a very complete index and a copy of the Brunner Depth, Time and Distance Chart for Deep Focus Earthquakes complete the volume. On the whole, the typography is satisfactory and but few errors could be found, all quite unimportant.

In spite of some of the criticisms raised in this review, the book is one of great value as a source book in the field it covers and can be read with profit by all interested in seismology, "applied" or otherwise.

M. M. SLOTNICK

THE SOCIETY ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The Executive Committee have approved for publication the names of the following candidates for membership in the Society. This publication does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualification of these nominees, he should send it to the Secretary within thirty days. (Names of sponsors are placed beneath the name of each nominee.)

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T. N. Walsh, J. E. Jonsson, E. McDermott

Carl Herman Gerdes
J. C. Pollard, G. Stubbe, Henry Cortes

Irving M. Griffin, Jr.
H. B. Peacock, H. Salvatori, O. D. Walling

John George Konigsberger
Accepted by the Executive Committee in accordance with clause III-C-1 of the Constitution.

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O. D. Kerns, G. P. Kerns, R. L. McLaren

Horace Strong Moore
J. J. Jakosky (Clause III-C-1 of Constitution)

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Socrates Shumilin
(Clause III-C-1 of the Constitution)

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James Clark Templeton
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T. L. Allen, O. S. Petty, F. B. Smith

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TRANSFER FROM ASSOCIATE TO ACTIVE

Norman James Christie
George Herman Rabson

THIRD MID-YEAR MEETING

of the

SOCIETY OF EXPLORATION GEOPHYSICISTS

November 19–20, 1937

Headquarters and Meetings, Rice Hotel, Houston, Texas

FRIDAY, NOVEMBER 19

9:00	Registration, Mezzanine floor
10:00–12:00	Technical Session of the Society
12:00– 1:00	Joint Luncheon of the S.E.G. and the Houston Geological Society—Rice Hotel
2:00– 5:00	Technical Session of the Society
7:30	Stag dinner—Rice Hotel

SATURDAY, NOVEMBER 20

10:00–12:00	Technical Session of the Society

FRIDAY, NOVEMBER 19

10:00–12:00 Technical Session—Chairman, M. M. Slotnick

Papers

1. A set of Curves to Assist in the Interpretation of the Three-Layer Resistivity Problem. W. W. Wetzel, Howard V. McMurry, (Geological Dept., Mass. Inst. Technology. Cambridge, Massachusetts).

2. On the Extension of Two-Layer Methods of Interpretation of Earth Resistivity Data to Three and More Layers. Robert J. Watson (Carter Oil Co., Tulsa, Oklahoma); James F. Johnston (Continental Oil Co., Tulsa, Oklahoma).

3. A Historical Review of Electrical Prospecting Methods. W. M. Rust, Jr. (Humble Oil & Refining Co., Houston, Texas).

4. On the Field due to a Vertical Line Source of Current Grounded to Earth. S. Bilinsky (Subterrex, Houston, Texas).

2:00– 5:00 Technical Session—Chairman, E. E. Rosaire

Papers

1. On the Strategy and Tactics of Exploration for Petroleum, II. E. E. Rosaire (Subterrex, Houston, Texas).

2. The Chester, Illinois, Slide—a Problem in Rheology. Paul Weaver (Gulf Oil Corporation, Houston, Texas).

3. A Military Aspect of Exploration Geophysics. E. Roane Melton (Seismic Explorations, Inc., Houston, Texas).

4. The Reflection of Elastic Waves from Transition Layers of Variable Velocity. Alfred Wolf (Geophysical Research Corporation, Tulsa, Oklahoma).

5. A Note on the Propagation of Seismic Waves. Morris Muskat (Gulf Research & Development Corporation, Pittsburgh, Pa.).

6. Improved Time Breaks with the New DuPont Beaded Type "SSS" Cap. L. W. Burrows (E. I. DuPont de Nemours & Co., Wilmington, Del.).

7. Seismic Exploration in Eastern Venezuela. W. R. Ransone (Geophysical Service, Inc., Dallas, Texas).

7:30 Stag Dinner—Tostmaster, J. C. Karcher

SATURDAY, NOVEMBER 20

10:00–12:00 Technical Session—Chairman, T. I. Harkins

Papers

1. Use of the Geo-Sonograph in Routine Exploration. Curtis H. Johnson (Rieber Laboratory, Los Angeles, California).

2. The Application of Fourier Integral Analysis to some Geophysical Problems. W. T. Born (Geophysical Research Corporation, Tulsa, Oklahoma); J. M. Kendall (Geophysical Research Corporation, Tulsa, Oklahoma).

3. Measurements of Relative Ground Motion in Reffection Recording. D. H. Gardner (Humble Oil & Refg. Co., Houston, Texas).

4. The Motion of a Geophone on the Surface of an Elastic Earth. W. T. Born (Geophysical Research Corporation, Tulsa, Oklahoma); A. Wolf (Geophysical Research Corporation, Tulsa, Oklahoma).

IMPORTANT NOTICE

Attention is called to the fact that applications for membership in the Society and other business matters of the Society are to be taken up, as heretofore, with the Secretary-Treasurer, M. E. Stiles, Independent Exploration Company, 2011 Experson Building, Houston, Texas. The appointment of a Business Manager has, for the present, been postponed and former notices of any changes are to be disregarded.